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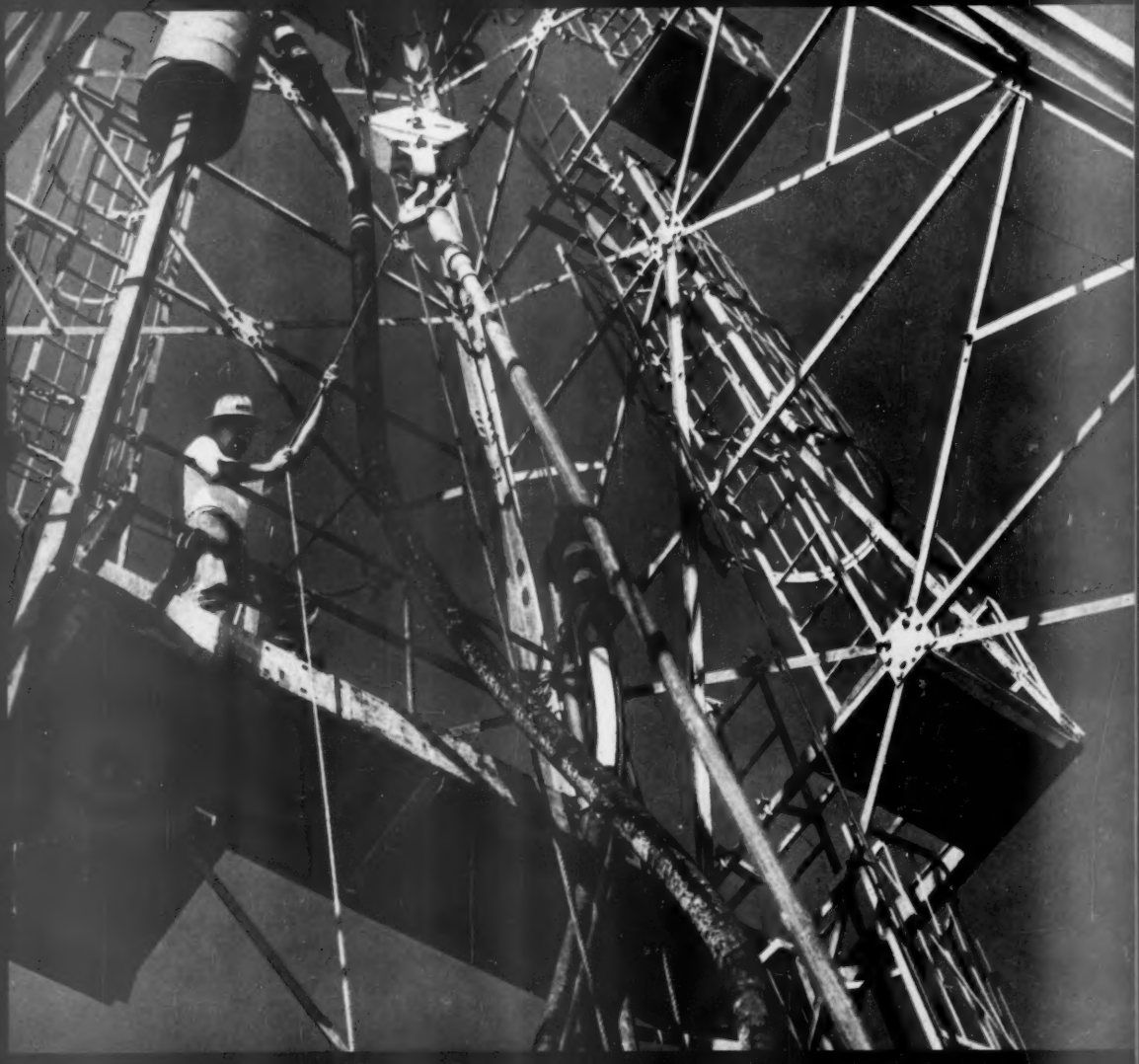

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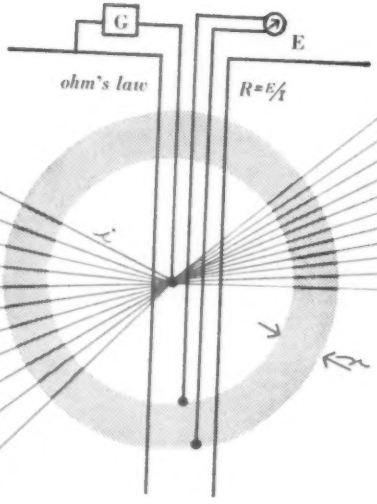

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On the Cover — A washing tool is guided to the finger board by an engineer at California Research Corp.'s model well. The set-up is located at the company's Oil Field Research Lab 25 miles east of Los Angeles. Full scale tools are used to drill and complete wells in artificial formations which are held in a pressure vessel 50 ft below the derrick floor. In the picture, weights on the kelly are necessary to prevent hydraulic ejection of the drill string through the rotary drilling seal. *(JPT Staff Photo.)*

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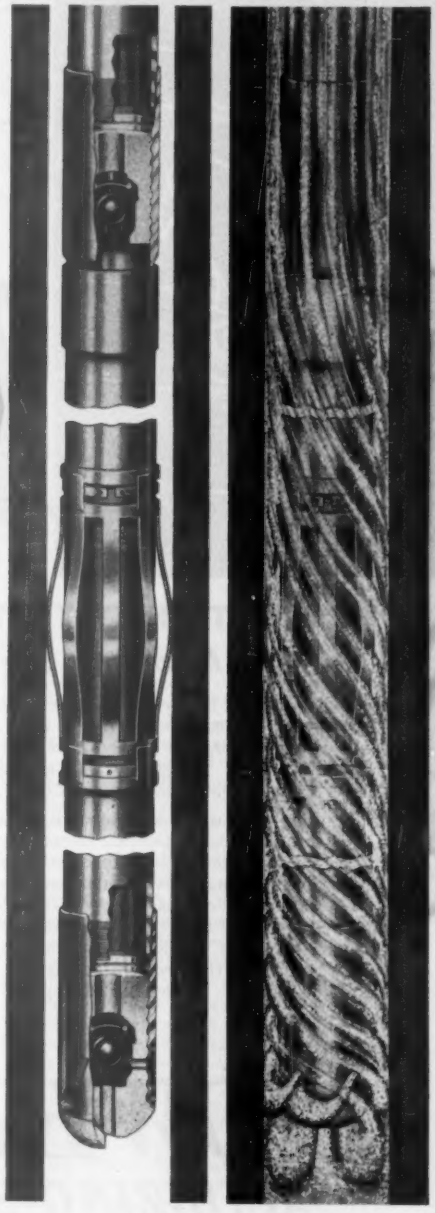

The view at far right shows the "whirling" motion given to the cement slurry as it is discharged from a Baker Cement Wash-Down WHIRLER Float Shoe, with the shoe joint centered by means of a Baker Model "G" Casing Centralizer. *This same whirling motion given to the circulating fluid, conditions and prepares the wall of the hole immediately prior to the discharge of the slurry.* The whirling action of the slurry, in turn, not only supplements the hole conditioning process, but also ensures that the centered casing will be completely encased with a uniform body of cement and that the hazard of channeling will be reduced to a minimum.

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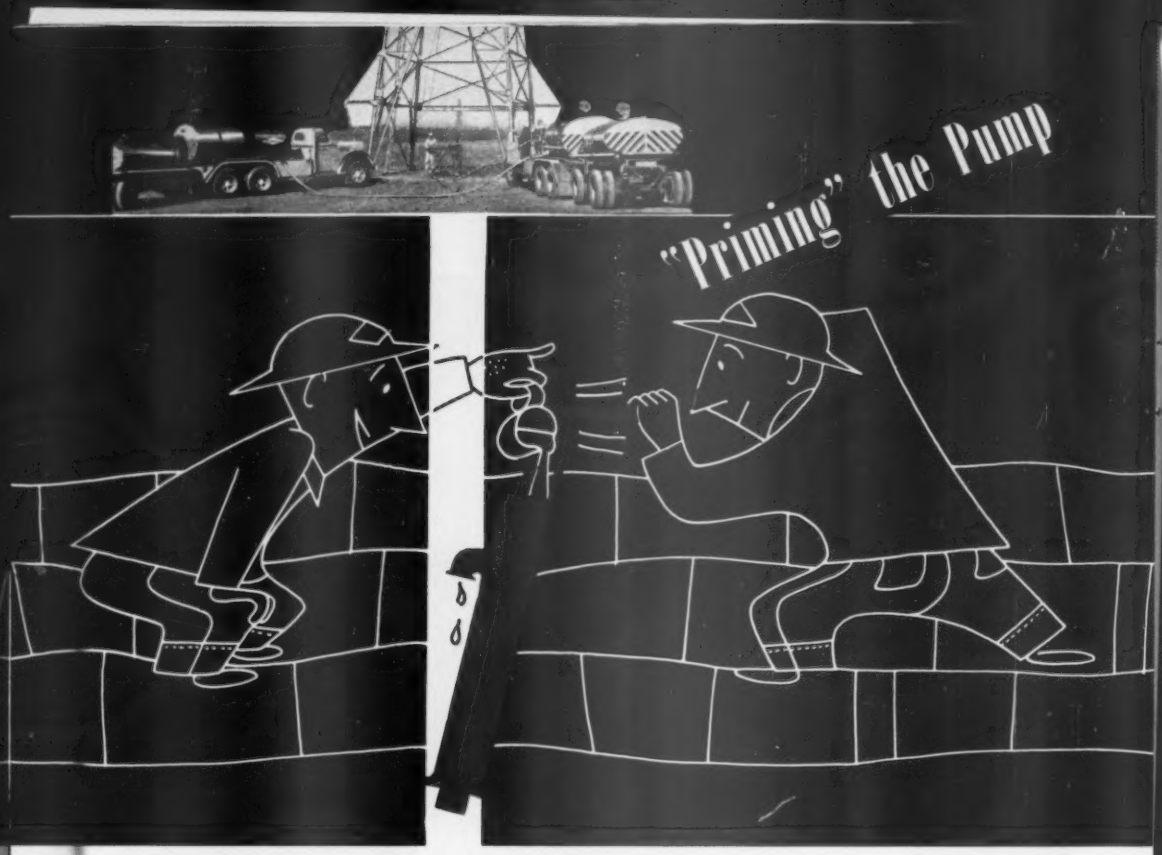

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Hydrafrac Operations in the *Spraberry*

By Waldo L. Grossman

Halliburton Oil Well Cementing Co.

FIG. 1 — LOCATION OF EIGHT-COUNTY SPRABERRY TREND AREA IN WEST TEXAS.

DURING late 1950 and up to present date in 1951 the Spraberry sand production of West Texas has created widespread interest in the oil producing industry. It is recognized that there are many controversial opinions concerning operations in the Spraberry, its economic value, and future development.

The application of Hydrafrac procedures to completion of Spraberry wells has become prominent in the development of these sands. This paper outlines the geology and historical development of the Spraberry and the use of Hydrafrac applications in these formations.

INTRODUCTION

The application of the Hydrafrac Process to wells completing from the Spraberry formation was begun during the latter part of 1950. The Hydrafrac Process consists of preparing a viscous gel to which a special sand is added and pumping this material into the producing formation at a rate which will develop sufficient hydraulic force to produce and/or extend a fracture. The gel must be of an unstable character to revert to a thin fluid, such that it may be recovered from the well, leaving the introduced sand in the fracture as a propping agent. In order to insure the reversion of gel to a fluid, breaker chemicals are mixed with crude oil and flushed into the formation behind the gel. The success of these treatments has been closely associated with the current expanding drilling and development program along an area commonly referred to as the "Spraberry Trend." "Top of Spraberry" is found at depths of 6,500 to 7,500 ft in most of this area.

This trend covers an area over 100 miles in length and 50 miles in width from the North Gail Field of Borden County to the Flatrock Field of Upton County. Location of this eight-county area of West Texas is shown in Fig. 1. Location of the fields discovered through June, 1951, are shown in Fig. 2.

First commercial production from the Spraberry was developed in the Spraberry Deep Field of Dawson County in January, 1949. In February of the same year, the Tex-Harvey Field was discovered. Although both produce from the Spraberry, many characteristics of the two reservoirs are considerably different. Since the Spraberry is a relatively new producing formation, many controversial opinions are held with regard to it.

This paper is presented to record the various manners in which the Hydrafrac treatment has been used for Spraberry completions and to report the trend of these various methods of Hydrafrac treatment. Sufficient information is not available at this time to prove conclusively which is the best method of treatment. In view of the trend of treatment technique, suggestions of possible formation reaction will be made for future observation and analysis.

GEOLOGY

The areal extent of the Spraberry sandstones is indicated in Fig. 1 as a rectangular area in which the eight-county "Spraberry Trend" is located.[1] They do not outcrop,[2] being similar in character to a giant sand lens.

The Spraberry sands are developed in the lower Leonard section of the Permian Series. The Spraberry section is generally 1,000 ft thick over the area of current development. The "Upper" Spraberry is generally 200 to 250 ft in thickness, containing three developed sandstones, with an average net sand development of 90 ft. The "Middle" Spraberry is 300 to 350 ft in thickness, primarily shale, with a total net sand development of less than 50 ft. The "Lower" Spraberry is similar to the "Upper," containing four developed sand members with an average net sand development of 170 ft.[3]

Both the "Upper" and "Lower" members have essentially the same lithologic characteristics.[3] They are very fine grained sandstones with thin streaks of limestones and shale.

A unique characteristic of the section is the existing vertical fracturing. The fractures are both vertical and parallel, consequently they are rarely interconnected in cores. The upper and lower limits of a fracture show no apparent relationship to lithology; they extend from sand to shale. Very little secondary deposition has been observed in the fracture system. This fracture development is not as prevalent in the Spraberry Deep Field as in the Midland, Glasscock, Upton, and Reagan County area. A photograph of a core exhibiting this type of vertical fracturing is shown in Fig. 3.

Table I — Method of Treatment Application

Month	Open Hole Treatments: Casing Packer	Open Hole Treatments: Formation Anchor Packer	Open Hole Treatments: Straddle Packer	Perf. Treatments: Casing Packer	Perf. Treatments: Straddle Packer	Total No. Treatments
1950						
Sept.	1	1	—	1	—	3
Oct.	—	—	—	—	—	0
Nov.	—	3	—	—	—	3
Dec.	5	5	17	2	2	31
1951						
Jan.	9	10	44	16	—	79
Feb.	4	18	22	7	3	54
Mar.	10	24	33	11	5	83
Apr.	25	31	36	4	4	100
May	22	37	33	3	10	105
June	24	23	53	11	3	114
Total	100	152	238	55	27	572

HISTORY OF DEVELOPMENT

Discovery of the North Gail Field in Borden County in March, 1949, followed closely that of the Spraberry Deep and Tex-Harvey fields. Development was relatively slow. During 1950, Spraberry discoveries were made of the Pembrook (Upton County); Germania (Midland County); Benedum-Spraberry (Upton County); Midkiff (Midland County); Huddle-Manning (Dawson County); and Smith-Spraberry (Dawson County) fields.

Through the first six months of 1951 discoveries include the Driver (Midland County); Glass-Spraberry (Martin County); Weiner-Floyd (Upton County); Snowden-Spraberry (Dawson County); Pembrook-North (Upton County); Weddell (Reagan County); and Aldwell (Reagan County). Location of these fields is shown in Fig. 2, an eight-county map of the "Spraberry Trend" area.

During the first half of 1951 the number of producers in 15 of these fields has increased from 63 to 316 and the monthly oil production from 172,561 to 678,720 bbl. A comparison of monthly oil production and the number of producing wells completed each month in these same fields with the number of all Spraberry Hydrafrac treatments during the same period is shown in Fig. 4. The first Hydrafrac treatment in the Spraberry was performed in September, 1950. However, the treatments performed in November, 1950, were responsible for the acceptance of the process for Spraberry completions.

Prior to this period, most wells were shot with nitro-glycerine to stimulate production; a few wells were treated with acid. Shooting with nitro-glycerine was very successful in the Spraberry Deep Field and results were good in the Tex-Harvey Field; however, due to differences between the fields, the clean-out problem in Tex-Harvey was more troublesome than in the Spraberry Deep. On the basis of average reported potential test data for 168 wells completed prior to June 15, 1951, in the Tex-Harvey Field; 43 wells completed by shooting ranged from 27 BOPD to 522 BOPD, with an average of 236.3 BOPD; whereas 125 wells completed by Hydrafrac treatment ranged from 21 BOPD to 803 BOPD, with an average of 314.6 BOPD.

DRILLING PRACTICES

Several different casing programs are being used in this area, both for reason of difference of opinion and because of the casing shortage. One method is to set about 300 ft of surface casing, 3,800 to 4,200 ft of intermediate casing and a 5½-in. or 7-in. full oil string. A second method includes the first two strings mentioned previously, followed with 5½-in. or 7-in. long liner for the oil string. A third method is to set 1,500 to 1,700 ft of surface casing, followed with a full 5½-in. or 7-in. oil string. A fourth method reduces the previously listed surface casing to 300 ft.

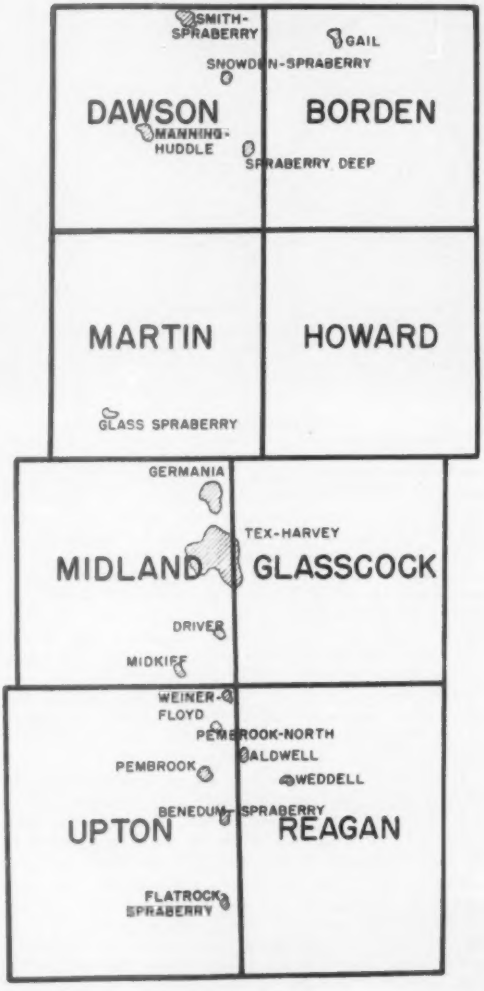

FIG. 2 — SPRABERRY SAND FIELDS THROUGH JUNE, 1951.

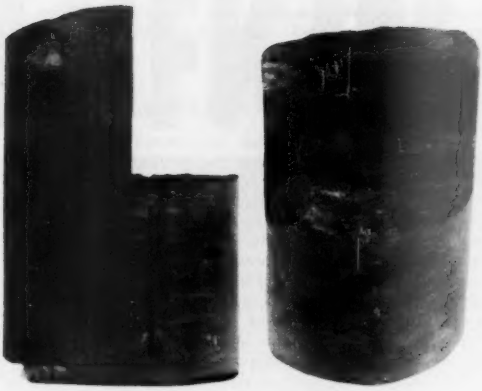

FIG. 3 — TYPICAL CORE OF SPRABERRY SAND, SHOWING EXISTING VERTICAL FRACTURE.

The oil string is generally set 30 to 60 ft above the expected "Top of Spraberry." However, in a few cases the oil string has been set at, or slightly below, the "Top of Spraberry"; or through the "Upper" or "Middle" Spraberry, or through the entire Spraberry section.

Drilling in for open hole completion is generally performed by rotary drilling, using Spraberry crude oil as a reverse circulating fluid. Cable tools also are used by some well owners and their use is on the increase. One well owner used compressed air as a reverse circulating medium with rotary drilling.

Water base and emulsion muds have proven generally unsatisfactory in the Midland, Glasscock, Upton and Reagan County areas. This is the area of greatest active drilling and also the area of most successful Hydrafrac completions.

The greatest part of the current development is in the "Upper" Spraberry. Most wells are either drilled 50 to 75 ft into the "Upper" Spraberry or are drilled through the complete 200 to 250 ft section. In a few wells completion has been from open hole in the "Lower" Spraberry and through perforations in the "Upper" Spraberry. Most of the treatments through casing perforations have been on wells in which casing through the Spraberry was necessary to test or produce a lower pay formation.

RESERVOIR CHARACTERISTICS

The Spraberry Deep Field is of the closed anticlinal structure type. The Germania, Tex-Harvey, Driver, Midkiff, Weiner-Floyd, Pembrook North, Aldwell, Pembrook and Benedum fields may eventually all connect together as one reservoir of the permeability-porosity type with possible closure in part of the Benedum area. Not only is the producing area undefined for the latter field, the top and bottom of the producing section has not been satisfactorily defined.

The permeability of Spraberry sand sections generally ranges from 0 to 10 md; occasional samples have been reported to run 70 to 80 md. The average probably is about 1 md. Average porosity ranges from 10 per cent to 15 per cent, with a high connate water content. Spraberry crude ranges from 38° to 40° API gravity; gas/oil ratios from 350 to 900; bottom-hole pressure from 2,100 to 2,300 psi.

Core analysis will not evaluate the fracture system. Cores may indicate loss of cement, mud or lost circulation materials into the fracture system. In one case cement was found over 50 ft below "Top of Spraberry" where casing had been set at TD of 30 ft above "Top of Spraberry." Drill stem tests may indicate production; however, a poor recovery on drill stem test is not sufficient to condemn the section tested. Electrically recorded surveys serve for correlation and sand development purposes; however, fluid content or productivity interpretations are not universally agreed upon.

METHOD OF TREATMENT APPLICATION

All Hydrafrac treatments of the Spraberry through June, 1951, have been performed with a packer in the well. Open hole treatments may be performed with several general types of packers:

1. Packer set in casing. Treat open hole below casing shoe to total depth.
2. Single formation anchor packer set in the open hole, generally treat from packer to total depth. Treatments of open hole above packer back to casing shoe has generally resulted in a fishing job.
3. Straddle type formation packer with one or both packer elements set in the open hole; treat open hole between two packer elements.

Treatment through casing perforations could be either of two types:

1. They may be either above or below a single casing packer. None have been reported performed above such a packer as of this date.
2. They may also be performed between straddle type packers.

A breakdown into these five classes is shown in Table I of all Spraberry Hydrafrac treatments by months through June, 1951. These data indicate the preference of open hole completion. Surface treating pressures are generally considered below normal for Hydrafrac treatment of wells 6,500 to 7,500 ft deep. This may be explained as a result of the existing fracture system in the Spraberry section. Oil generally is pumped into the formation prior to Hydrafrac treatment at pressures

Table II — Size of Hydrafrac Treatment

Month	Amount of Gel Fluid — Gallons								Total No. Treatments
	750	1,500	2,250	3,000	3,750	4,500	5,250	6,000	
1950									
Sept.	—	3	—	—	—	—	—	—	3
Oct.	—	—	—	—	—	—	—	—	0
Nov.	—	2	1	—	—	—	—	—	3
Dec.	—	17	14	—	—	—	—	—	31
1951									
Jan.	1	62	16	—	—	—	—	—	79
Feb.	—	41	7	6	—	—	—	—	54
Mar.	5	57	4	16	—	—	—	1	83
Apr.	3	57	7	30	2	1	—	—	100
May	—	63	6	27	1	4	1	3	105
June	2	61	9	26	1	13	—	2	114
Total	11	363	64	105	4	18	1	6	572

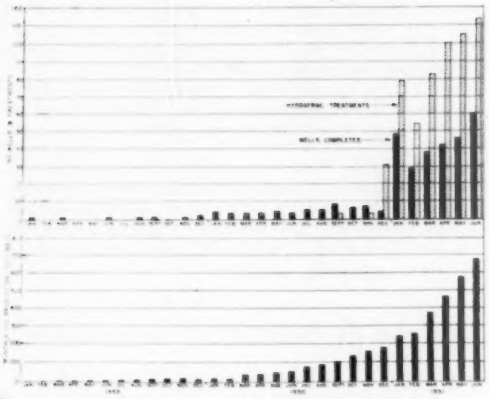

FIG. 4 — COMPARISON OF MONTHLY OIL PRODUCTION AND NUMBER OF ALL SPRABERRY HYDRAFRAC TREATMENTS DURING SAME PERIOD.

from 600 to 1,800 psi. Average is about 1,000 psi. Maximum treating pressure ranges from 1,500 psi to 3,500 psi. Average is about 2,500 psi. Average injection rates of three to four bbl per min are generally maintained during Hydrafrac treatment.

SIZE HYDRAFRAC TREATMENT

The first few Spraberry Hydrafrac treatments were performed using 1,500 gal of gel fluid. Some well owners soon began using larger volumes of gel fluid per treatment. The number of treatments for each size treatment by months through June, 1951, is listed in Table II. These data show the trend upward toward large size treatments and also indicate that less than a 1,500 gal treatment is probably not desirable. In this area 750 gal of gel fluid mixed with 400 lb of sand, followed by 1,500 gal of crude oil, mixed with breaker chemicals, is considered a normal single batch of chemicals for Hydrafrac treatment.

The first change in treatment was to increase the number of batches used. The second change was to increase the amount of sand to 600 or 800 lb per batch for some treatments. During June, 1951, the amount of sand used averaged about 500 lb per batch for all treatments. The next change was the reduction of breaker chemicals. Satisfactory results have been obtained by reducing the volume of breaker fluid used by one-half. Another technique has been to displace the gel only into the formation with crude oil mixed with breaker chemicals. This practice has not been fully evaluated and is not recommended for any other producing formation at this time.

RE-TREATMENTS

Re-treatments have been of two general types. First, zones have been re-treated a few days after initial treatment. The second treatment is always a larger volume than the first treatment. In a few cases, the second treatment has increased production sufficiently over that resulting from the initial treatment to result in a commercial well.

The second type of re-treatment is that performed on wells which were completed as commercial wells after the original treatment. If, after producing several months, these wells no longer are capable of making their allowable production, re-treatment with increased volumes of gel fluid has been successful.

THEORY OF TREATMENT

The Hydrafrac treatment has been proven as a method of stimulating oil production from the Spraberry section. Why and how does it work? An answer to this question should result in better well completions.

Pumping crude oil, or kerosene, has been tried without commercial success in the Spraberry. What is the difference between the Hydrafrac treatment and an oil squeeze? Primarily, Hydrafrac gel fluids have very high viscosity which enables the suspending and pumping into the formation of a specially graded sand. As a result of these differences several proposals may be made as to what happens to the formation as a result of a Hydrafrac treatment:

First, the existing fractures may be further opened and held apart by the sand grains introduced into the formation in the gel fluid. Second, the existing fractures may be extended and both original and extended fractures held apart by the propping agent. Third, the existing fractures and extensions may be enlarged due to the abrasive action of the propping agent introduced in the gel fluids at high velocity. Fourth, due to the peculiar nature of vertical and parallel fracturing, transverse breakage may occur from fracture to fracture due to the bending applied to these layers in the vicinity of the bore hole. The high viscosity, low fluid loss characteristics and sand may all be factors which allow the necessary bending force to be applied to these layers.

CONCLUSIONS

The Spraberry formation of West Texas is proven as a great oil reserve. The problem of producing this reserve with financial gain for the well owner is a matter of considerable concern to many people. Additional experience in the several means of Hydrafrac application will better enable evaluation as to the best possible method of treatment.

ACKNOWLEDGMENT

The writer expresses appreciation to the management of the Halliburton Oil Well Cementing Co. for permission to write this paper.

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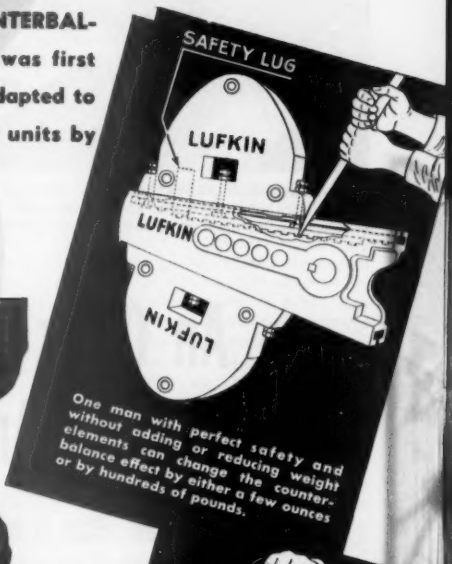

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How to proceed: Instructions on how to submit ideas under the Sinclair Plan are contained in an Inventor's Booklet available on request. Write to: W. M. Flowers, Executive Vice-President, Sinclair Research Laboratories, Inc., 630 Fifth Avenue, New York 20, N. Y. for your copy.

IMPORTANT: *Please do not send in any ideas until you have sent for and received the instructions.*

SINCLAIR—A Great Name in Oil

Utilization of RESEARCH In Production of Oil

By John E. Sherborne
Union Oil Co. of California
Member AIME

There is considerable evidence in support of the proposition that several thousand years ago, Noah, in plying the Euphrates River in his ark, was pursuing his usual trade of being a merchant seaman; and that, in times of normal rainfall at least, part of his cargo was bitumen from the large deposits which occur along the river's banks. For this tarry substance he found a good market among the Egyptians who had discovered it to be useful in caulking their boats.

Undoubtedly, earlier uses of petroleum were discovered as a result of man's curiosity and his readiness to adapt his findings to improving his welfare. The significant fact that man not only had curiosity but the aptitude to classify and utilize the observations, both physical and mental, which his curiosity led him to make, is the basis for the tremendous increase in our fund of knowledge since Noah's day. Couple this research, the orderly effort resulting in new knowledge, with man's enterprise and there exists the basis for business growth.

It is a far cry from the business in which Noah engaged to the vast industrial enterprises of today and, in like manner, industrial research has emerged from equally humble beginnings until today it must in itself be classed as big business. According to the best available estimates, the petroleum industry is currently spending over $100,000,000 annually for research. Equally significant is the fact that since 1947 more than a dozen multi-million dollar laboratories have been built by the petroleum industry, many of which have been especially for the pursuit of research in oil production.

Research management, like the general industry management of which it is a part, in initiating and pursuing research, must have as its objective the increasing of the profitability of that industry's operations. That research has proved profitable to industry is a fact which no informed person will dispute. It is the object of this discussion, however, to explore ways in which research can be made yet more profitable.

MAKING RESEARCH MORE PROFITABLE

One important means of increasing the profitability of research is in improving the relationship which exists between research, engineering, operating and management personnel. For industrial research to be profitable, it must be utilized, and for optimum utilization to exist, members of each of the above industrial groups must engage in "team thinking." For members of the several groups to behave as a team, each member must be cognizant of the others' functions and appreciate the scope and importance of them. Each must understand the basic requirements for the solution of the others' problems, and must familiarize himself with the others' approach to the solution of their problems.

Research personnel can improve their usefulness to the engineer if, during the course of their investigations, data gathering is conducted in such a manner that the significant variables are examined over a range of conditions which can be expected to encompass those which will exist in practice. Such information adequately correlated can save the engineering staff much labor and will materially minimize the degree to which the engineer must resort to estimate and assumption.

Those engaged in research will also do well to examine the direct approach used by the operating man, the techniques he has developed for planning and coordinating the variety of diversified but related activities which constitute his operations, and the extent to which he utilizes equipment to increase the effectiveness of labor. The research man will profit too by a better understanding of the factors which motivate management—by being more cognizant of what part his project plays in the company's activities, what its cost is relative to the other expenditures which must be made, what its successful completion can mean to the company, and how changing conditions can affect the outcome of a particular research project. More than once research men have been encountered who, having successfully completed a project, were dismayed to find that no plans for the current utilization of the results of their work existed at the time. While there may be some instances in which the starting of such a project was bad management, in most such cases it is highly likely that excellent reasons existed for starting the research initially and for continuing it, but that conditions prevailing at the time of culmination did not permit commercial application at that particular time.

It is more generally true than not that developments likely to yield large profits require large scale operation and sizable expenditures of funds in order to commercialize them. As a consequence, management must consider carefully the commercial application of a new development in the light of a number of factors. Some of the more significant of these are the company's financial condition at the time, the market situation with respect to the material or process resulting from the research, the merit of the development

relative to that of other proposals which must be considered by management, and the probable impact that other technical developments may have upon its commercial application. In the case of oil production, commercial utilization of a new proposal often means that not only must management be convinced of its profitability, but, in addition, operating partners, land owners, neighboring operators and their land owners, and government agents must also be educated and convinced of the value of the development before it can be applied. Management has a responsibility to the research man to foster his interest in these factors, and while it cannot be expected that an explanation of the specific details leading to a particular decision regarding a project will always be forthcoming, research personnel should, whenever possible, be as fully apprised as is reasonable of the factors bearing upon the decision.

Similarly, members of the other groups must bear in mind that by the very nature of the problem assigned to him, the research man does not usually have available techniques and tools proved by past use to be the most satisfactory for a particular operation. The operating man knows from previous experience which of the equipment and procedures available will be most suitable for preparing a rig site, for example, and can feel reasonably confident that once he has selected the tools and plan of attack, the job will be accomplished with dispatch. Even a piece of new equipment not heretofore tried by him has usually had a long history of development by its manufacturers before being submitted for use by the operating man. Often, however, in research it is not only necessary to develop a suitable procedure but to design adequate equipment also. Furthermore, the development of a suitable procedure will more likely than not require that several alternative approaches be explored before a satisfactory one is found. Nearly always, certain basic data must be gathered, either by a painstaking survey of the literature or by actual performance of research, before an adequate foundation for the applied research in question can be obtained. It is also natural for research men to interest themselves in new scientific discoveries and, if they are performing their jobs properly, they will continually evaluate such new developments in terms of what these can mean to the company. These discoveries may be the product of other research laboratories or they may result from the researcher's own efforts. In either case, proper evaluation of them frequently requires that a certain amount of reconnaissance be performed. In such instances, the scientist and his supervisors must be cautious that the project to which he was assigned, and for which it has already been determined that the company needs an answer, is not unduly neglected. Many times these considerations result in suggestions of research which might profitably be undertaken by the company; however, it is often necessary to consider such projects as long range undertakings. Here again the research director can be aided by group opinion in properly orienting the new proposal with respect to its relative significance as compared with projects currently being pursued.

VALUE OF "TEAM THINKING"

It seems reasonable to expect that for a company, in which the members of the several groups have improved by adequate liaison their mutual understanding and confidence to the extent that "team thinking" is practiced, increased utilization of research will be achieved by:

1. Initiation of projects most likely to prove profitable to the company.
2. Preserving a balance suitable to the company's needs between long and short range projects.
3. Decreasing the lag which exists between discovery and development on the one hand and application on the other.
4. Providing a basis for joint solution of problems where larger than laboratory or field-scale experimentation is necessary.

It should not be implied that because a company has "team thinking" it can be expected that all of its research projects will be successful. In a way, research is like wildcatting. There are two ways in which an oil company can increase its reserves. One is by obtaining new oil fields. Another is by improving the efficiency of recovery and developing new ways of recovering additional oil from its present oil fields. In setting out to look for new fields, the geologists generally consider many more plays than they have funds available with which to explore, and presumably choose from among these plays only those which appear to have the greatest probability of being profitable to the company.

In research, a similar situation exists — there are always more projects which show promise of being profitable than those for which funds are available. Consideration of these projects by members of the several groups will insure that the director of research will have the benefit of the several points of view in the choosing of those projects most likely to fit the company's needs.

This close coordination serves to acquaint the operating men with the need for long range research and the research personnel with a knowledge of problems for which there is required an immediate solution. Thus, a suitable balance between long and short range projects can be maintained. In considering what this balance should be, thought must be given to the nature of the company's business, whether or not it is a continuing business — one which is looking forward to a long life, or one which is undergoing substantial metamorphism. A company's financial situation at any given time and a prognostication of what its probable financial situation will be over a period of time must also be considered. Obviously, it would be foolish to embark upon a project which required for its solution a long period of time no matter how promising it appears, if the company's financial condition were such that the project would have to be abandoned for lack of funds before it could be completed. On the other hand, a business expecting to remain operating for a long period of time must of necessity consider prosecuting research which will answer the question, "What are we going to do when we can no longer do profitably what we are now doing?" It need not be unduly stressed that the research effort necessary for the answering of this question should commence at a sufficiently early date to permit a comfortable margin between the obtaining of the answer and the deadline which exists.

It has been the writer's observation in studying research in industry that a lag of several years frequently exists between conception and development of an idea and its final application in the field. It is in decreasing the lag between discovery and application that there is believed to be an area for increasing profitability of research. It would appear that a number of ways exist for decreasing this lag, some of the more significant of which are:

1. By improving the liaison between departments and between individuals in different departments, *i.e.*, by fostering what has been described as "team thinking."
2. Research personnel must continue to improve their ability and increase

their effort to put their findings into reports which are concise, logically constructed and simple in language. As Howard C. Pyle[1] has observed, research men should, in talking about their work, treat the subject with enthusiasm. They should avoid the use of "six-bit words" and should refrain from introducing into the communication interesting phases of their work that are unrelated to and detract from the main discussion.

3. In writing research reports, attention should be paid to its intended readers, and its content should be arranged accordingly. Reports to members of management or operating groups should be presented in nontechnical terms, with such supporting technical data as are necessary confined to appendices to the report.
4. Research men should be prompt in acknowledging requests made of them by members of other departments and in executing the work required. In a like manner, for cases where it has been agreed that such are necessary, engineers and operating men should be prompt in arranging for pilot and field-scale experiments.
5. For projects which cannot be completed in a short period of time, the research department should issue periodic reports indicating to the departments involved the progress which is being made on the research.

Ability to win confidence and to sell the results of one's work and a readiness to accept and to put into application new ideas are characteristics which all members of industry can well afford to develop. According to James C. Zeder,[2] "A research head has one of the most frustrating jobs in the world — selling new ideas to people who are operating successfully with old ideas — and he must not only have the courage of his convictions but also the salesmanship necessary to get them accepted by his management." It goes without saying that this applies also to the research man in dealing with any of the members of other departments to whom he must sell his idea. This serves to emphasize once more the importance of building mutual confidence between the members of the several groups which must produce and utilize research.

Another way in which the utilization of research can be made more profitable is by acceptance of the concept that there is a "level of intensity" of effort below which it is unlikely that a project can be successfully culminated. Obviously, it would be unwise to attack a problem for which an answer must be had in, say, five years at a rate of activity which will require ten years for its completion. It is particularly easy in setting up research budgets and in considering new research projects to ignore this point. Consideration of the concept of "level of intensity" in research suggests that attention should be called to the fact that there are a number of areas of production research for which there is a sufficient paucity of fundamental data that the necessary applied research cannot proceed in any one laboratory with an adequate intensity of effort. Here, it would seem that not only is increased cooperation within a company advantageous, but that cooperative research on an industry-wide scale would lead to more profitable utilization of research. It is true that the industry, by sponsoring activities of the American Petroleum Institute, the Natural Gas Association of America, and similar industrial organizations, has initiated a number of profitable cooperative research projects. It is the writer's belief that considerable opportunity exists to enhance applied research by extending inter-company research to include a greater number of such projects, but these must be carefully considered, well directed, and closely coordinated. In all such cooperative projects, adequate liaison and follow-through must be maintained by the member companies. How useful the results of such projects will be to an individual company will depend almost completely on the degree to which it assists through its representative in keeping before the project director the broad objectives to be achieved and in adapting the results of such projects to its own applied researches.

Besides maintaining an adequate "level of intensity," attention should be paid to preservation of the continity of research if such efforts are to provide the greatest yield. Research directors should bring to the attention of management the full implications of embarking upon a new project. Not only should the potential rewards be enumerated, but the financial burden and the scale of the undertaking should be delineated as clearly as possible. Research personnel should avoid the temptation markedly to expand their activities when profits are high; and, likewise, management ought to refrain from severely curtailing research when profits are low, if the company is to utilize its research to the fullest extent. While the research department should grow with the steady growth of the company, its activity should not fluctuate barometrically with the pulse of business activity. An examination of the records of a number of companies shows that the rate of growth of a company having an effective research department is a function of the amount it spends for research. It seems reasonable therefore, to postulate that the research effort be geared to the rate of growth permitted by a company's condition averaged over a period of years rather than to such arbitrary indices as gross sales and the like.

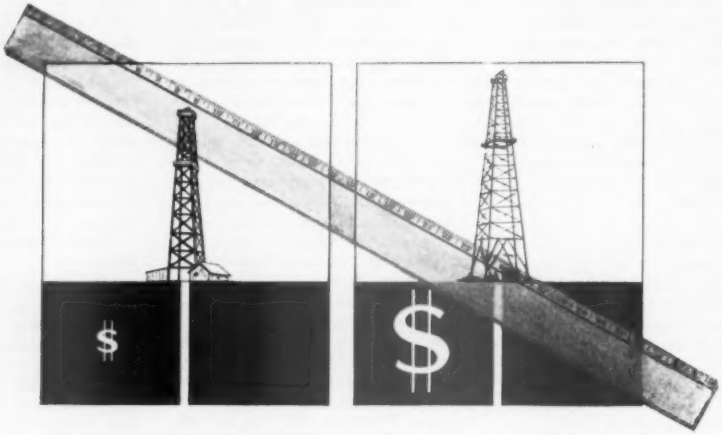
Furthermore, there is a widespread tendency among members of management to admonish supervisors to cut costs. It is realized, of course, that in most instances when such exhortations are made, what is really meant is that care should be taken to insure whatever money a company has to spend will be used in as wise a manner as possible. When it is necessary to cut expenditures, careful consideration must be given to the relative profitability of one expenditure as compared to another. Failure to do this can result in neglect or abandonment of operations which would ultimately result in greater profit than those which are continued. Possibly a better slogan than "cut the cost" would be "increase the value" of expenditures so that more can be had for less. It is even more important for management to be accurate in stating its objectives than it is for the scientist and engineer to refrain from jargonizing with technical terms their reports to management.

MECHANISMS FOR IMPROVING UTILIZATION

So far, the discussion has centered around desirable means of increasing the utility of research with little specific discussion of how to bring it about. There are a number of mechanisms being used within the industry today for bringing about improved utilization of research. Some of those which appear to have proved particularly beneficial will be discussed. One approach which has been adopted has been the use of research sponsoring committees as a means of bringing interested members of each of the several departmental groups together. In one company with which I am familiar, these committees operate on several levels, there being a top management

Continued on Page 7, Section 2

BY ANY YARDSTICK ... CEMENTING PRICES ARE LOW



DRILLING COSTS

Writing in a leading oil journal, a production executive of one of the world's largest oil companies makes the statement that "the average well-drilling costs have more than doubled in the last 10 years." The increase, he says, is the result of higher wages, higher investment costs of equipment, higher cost of materials and supplies, and the greater average depth of wells.

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West Coast Fall Meeting

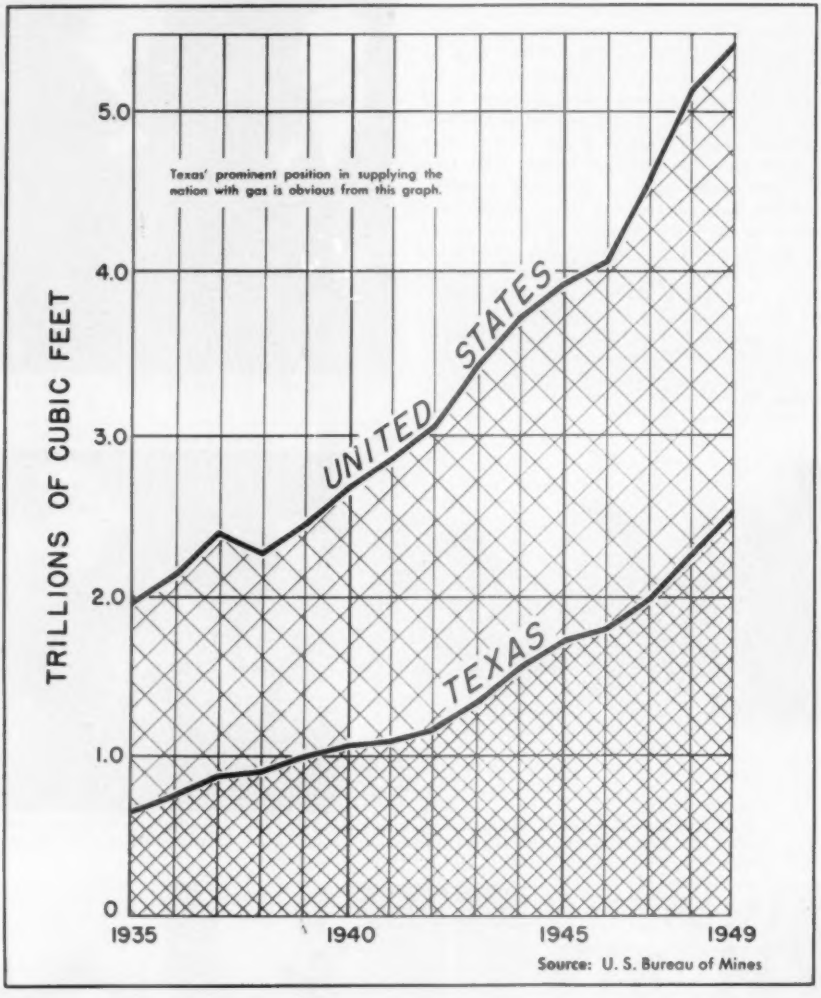
The West Coast Fall Meeting of the Petroleum Branch, AIME, held Oct. 26 and 27 in Los Angeles' Elks Club, attracted 312 members and guests from the Southern California area. A program of 14 papers assured good attendance at all technical sessions. At the Pacific Petroleum Chapter luncheon, California members heard Richard W. French, Branch chairman, speak on the state of the Petroleum Branch. AIME President W. M. Peirce spoke briefly on Institute-wide matters. The entire meeting, although presented by the Pacific Petroleum Chapter of the Petroleum Branch, was held in conjunction with the Metals and Mining branches, both of which had a minor program of papers. For the first time at a Petroleum Branch meeting, exhibitors competed for honors. Awarded first prize for the best exhibit was Lane-Wells Co. Second and third prizes were awarded McCullough Tool Co. and Eastman Oil Well Survey Co. At the Chapter luncheon, Wayne Glenn, chairman of the program committee for the meeting, was elected chairman of the Pacific Petroleum Chapter for 1952. The meeting was concluded with a dinner-dance in the Mayfair Hotel.

M. L. Haider, president-elect of the Institute, left, chats with Wayne Glenn, program chairman, during a break in the technical sessions. Glenn was elected chairman for 1952 of the Pacific Petroleum Chapter, hosts for the meeting.

Seated at the head table of the Chapter luncheon in Los Angeles' Town House are Edward H. Robie, AIME secretary; M. L. Haider, Richard W. French, Petroleum Branch Chairman; Basil Kantzer, chairman of the host Chapter; and W. M. Peirce, AIME president. At right, members register for the two-day meeting.

Winner of the first annual Exhibits Contest was the display offered by Lane-Wells Co. Other winners were exhibits of McCullough Tool Co. and Eastman Oil Well Survey Co. At right, members chat during Chapter luncheon at the Town House. Branch Chairman Richard W. French spoke briefly on Branch affairs.

MARKETED PRODUCTION OF NATURAL GAS



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Reported by D. B. O'Neill, Jr.
Pacific Petroleum Chapter

The pattern for successful management was proposed more than 3,000 years ago in the form of Jethro's advice to Moses when the former counseled Moses to select a number of able, God-fearing, truthful men to be rulers of thousands, hundreds, fifties and tens, and bring only the important matters to Moses for final decision. This pattern remains unchanged today.

With this thought introduced, S. F. Bowlby, vice-president of Shell Oil Co., proceeded to enlighten members of the junior and senior groups of the Pacific Petroleum Chapter on their chances of developing necessary attributes for key managerial positions.

Bowlby addressed his remarks primarily to the younger technical people, since many of them seem to be concerned about where they are going and how to get there. He said that while engineering and management inevitably grade into one another, engineering is the application of the natural sciences while management of that application is an art. Furthermore, although it is well known how a person may become an engineer, he stressed that there is no sure road to managerial success. Bowlby defined a manager as "one who accomplishes the desired end through others, using responsibility and authority delegated to him by the owners, to whom he is accountable." The three magic words of management, then, are authority, responsibility and accountability.

After a variety of engineering and managerial assignments in Oklahoma, Texas and Louisiana and in Europe, Bowlby became, in 1940, chief exploitation engineer for Shell, in Los Angeles. After other managerial positions in California, he was appointed vice-president in charge of exploration and production for his company's western operations in 1946, at the age of 41 — one of the company's youngest vice-presidents. In 1949, he was named regional vice-president in charge of exploration and production for the West Coast and Rocky Mountains.

He used the American petroleum industry's phenomenal growth and development during the past 50 years as an example of what he felt to be the "persistent application by its managers of sound engineering principles to a business where free enterprise and competition have thus far been unsurpassed." He felt, also, that an additional aid in the success of management in this industry was the application of the engineering method in making decisions. This method, Bowlby stated, consists of five steps: (1) clearly defining the problem, (2) getting all the facts, (3) working out alternative solutions to the problem on the basis of the facts, (4) choosing the best solution, and (5) following through to see that the chosen solution gets the job done. It is his contention that, without such planning on the part of management, the American petroleum industry could not have realized the remarkable growth it has seen, nor would it presently be capable of fulfilling the needs of the nation as it is doing today.

S. F. BOWLBY

Inasmuch as the engineering method is widely used by management today, it should follow, Bowlby felt, that engineers trained and experienced in the application of this method should be looked upon by the oil industry as the major source of future managers. However, Bowlby emphasized that the opportunity and demand exist especially

Continued on Page 3, Section 2

Branch to Continue Publication Of Annual Statistics Volume

In a recent survey of the membership of the Petroleum Branch, AIME, 67 per cent of the membership voted to continue publication of the volume, *Statistics of Oil and Gas Development and Production*. Previously, it had been proposed that publication of the volume be suspended. The survey also revealed that 36 per cent prefer to finance the publication through a provision in the annual Branch budget, 39 per cent prefer financing it from sales of the volume to users and 15 per cent voted to solicit subscriptions from industry.

As a result of these findings, Branch Chairman Richard W. French said: "(The) Branch Executive Committee considered that the vote . . . represents the majority of the membership and accordingly established a member-price of $5 per copy on the Statistics volume, effective with the volume covering 1951. The non-member price will be $10. Approximately $5,000 income will be secured through sales to users and the remaining $5,000 (necessary to finance publication) will be provided through the annual budget of the Branch. The Committee believes this is the action that will satisfy the largest number of members."

He pointed out that if a person wishes to order a copy or copies of the volume covering 1951, he should do so when paying his 1952 dues by simply adding the proper amount ($5.00 per copy) to his check and statement. The volume will be published late in 1952.

The current volume covering 1950 is now in the process of publication and will be distributed free to those Members, Associate Members and Junior Members who request it. Student Associates are not entitled to a free copy of the volume. Chairman French urged those who wish a copy of the volume covering 1950 but who have not indicated this desire to do so immediately by contacting the Petroleum Branch office at 408 Trinity Universal Bldg., Dallas 1, Tex. ★ ★ ★

Petroleum Industry Smog Research in California

Reported by Herman Dykstra
Pacific Technology Group

Efforts by the petroleum industry to alleviate the smog problem were outlined before the Pacific Technology Group in the seventh lecture of the current series on research, being held in the General Petroleum Auditorium in Los Angeles. V. N. Jenkins, research supervisor for the Union Oil Co., was speaker. At a later meeting, Reed C. Lawlor, patent attorney, discussed the nature of patents.

In reviewing the history of the air pollution problem in the Los Angeles Basin, Jenkins said that the petroleum industry was blamed for a considerable part of the smog problem, though there was no definite proof that the petroleum industry was responsible.

Executives of companies representing the petroleum industry in the Los Angeles area realized that something had to be done to show the public that the petroleum industry was doing its part to reduce air pollution. Consequently a committee was formed of representatives from major oil companies. This committee is now known as the Committee on Smoke and Fumes of the Western Oil and Gas Association. In December, 1946, the committee set up the following four-point program:

1. To determine the composition of smog.
2. To determine to what extent the Los Angeles Basin refineries are responsible for smog.
3. To develop the information necessary for the refineries to plan the steps which would have to be taken to reduce their contributions to smog.
4. To compile the data obtained and turn them over to those in charge of public relations for the industry.

It was soon realized that the first point would take a large amount of research that could not be handled by the committee alone. Consequently Stanford Research Institute was engaged to carry out the research on the composition of smog.

After the development of apparatus and methods for analysis, the institute analyzed a large number of air samples for particulate matter and gaseous pollutants. The number of particles in the Los Angeles atmosphere was found at times to be as high or higher than 10,000 per cu cm. Concentration (in ppm) of gaseous pollutants on a typical smoggy day were about as follows: sulfur dioxide, 0.1; nitrogen oxides, 0.2; organic chlorides (calc. as Cl_2), 0.1; ammonia, 0.1; aldehydes ($HCHO$), 0.3; volatile organics, 0.0; and oxidant (O_3), 0.35.

The Los Angeles Basin has become heavily industrialized in recent years. The Basin has the highest ratio of automotive vehicles to population of any area in the world. In addition about 880,000 backyard incinerators are present. The result is that each day some 40,000 tons of fuel gas, fuel oil, gasoline, diesel fuel, and coke and 10,000 tons of waste paper, garden clippings, leaves and wood waste are burned in the area.

Petroleum refiners represent only a part of the industry in the Los Angeles Basin. Obviously then they cannot be responsible for all of the smoke and fumes present in the atmosphere. Nevertheless, the refiners are doing their part by removing sulfur dioxide and hydrocarbon vapors from their waste gases. Meanwhile, the Committee on Smoke and Fumes, which is supported by the refiners, continues to pour money into research in an attempt to discover the true nature of the most objectionable features of smog, and hence how to reduce them to a tolerable level.

Lawlor, in the eighth lecture of the series, showed how our system of patents is derived from the constitution, which provides for protection of inventors in Article I, Section 8. The ultimate goal of this protection is to enhance the progress of science and the useful arts.

After making a few general remarks about patents, Lawlor outlined the following requirements for the filing of patents:

1. Application must be filed in the name of the inventor.
2. Inventor is often the one who has the idea and not usually the mechanic who merely follows the instructions of the one who has the idea.
3. One man should be designated as the inventor, if possible, in order that fellow workers may serve as witnesses.
4. Application must be filed within one year of publication anywhere or public use or placing on sale in the United States.

There are three kinds of patents—mechanical, design, and plant. Mechanical, or utilitarian patents, have to do with mechanisms, equipment, chemical and physical processes, or chemical composition. Design patents refer to art or ornamentation. Plant patents refer to the discovery of new plants, produced, for example, by hybridizing.

Four yard-sticks to determine whether an improvement is patentable are:

1. Subject matter. An idea cannot be patented, but the method of use, application, or embodiment of an idea

Continued on Page 6, Section 2

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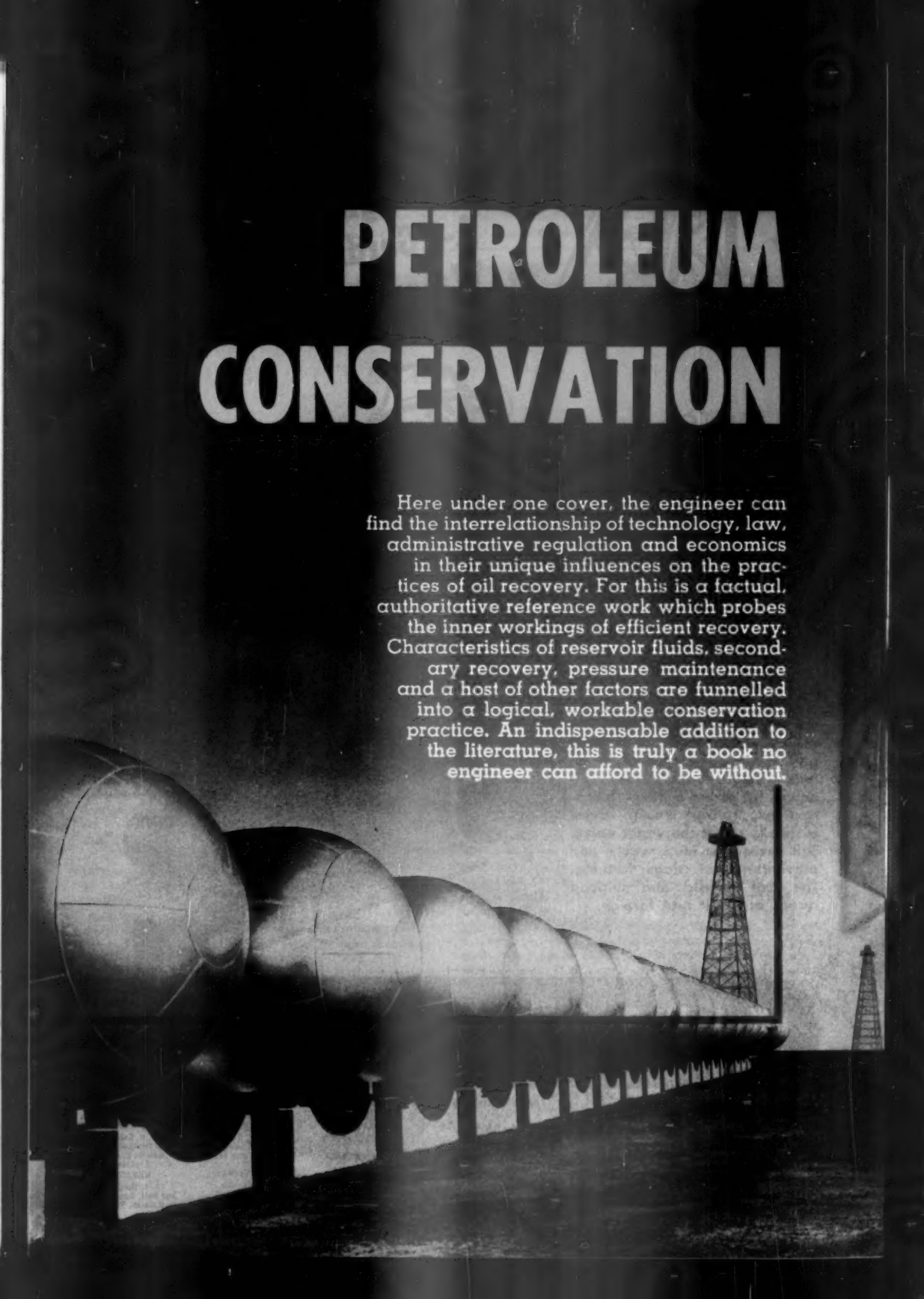

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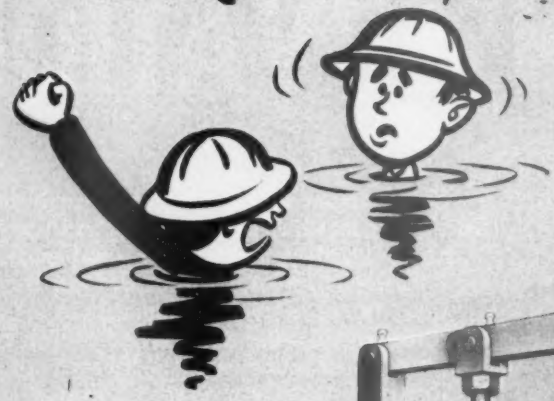

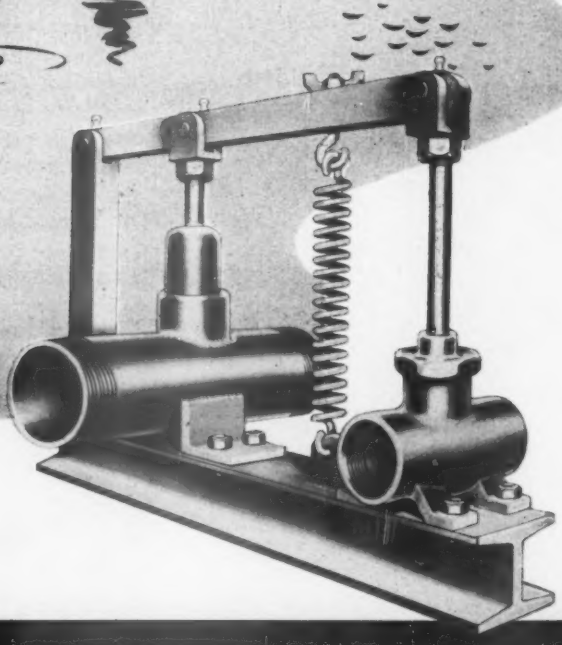

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DISCUSSION OF THIS AND ALL FOLLOWING TECHNICAL PAPERS IS INVITED
Discussion in writing (3 copies) may be sent to the Editor, *Journal of Petroleum Technology*, 408 Trinity Universal Bldg., Dallas 1, Texas, and will be considered for publication in the Transactions volume *Petroleum Development and Technology*. Discussion will close December 31, 1951. Any discussion offered thereafter should be in the form of a new paper.

AN EXPERIMENTAL AND THEORETICAL INVESTIGATION OF GRAVITY DRAINAGE PERFORMANCE

P. L. TERWILLIGER, JUNIOR MEMBER AIME; L. E. WILSEY; AND HOWARD N. HALL, P. M. BRIDGES AND R. A. MORSE, JUNIOR MEMBERS AIME; STANOLIND OIL AND GAS CO., TULSA, OKLA.

ABSTRACT

Theoretical and experimental investigations of a constant pressure gravity drainage system are reported. Experimental data are presented to show that recovery to gas breakthrough by gravity drainage is inversely proportional to rate. The gravity drainage reference rate, which is numerically equal to the so-called "maximum theoretical rate of gravity drainage" is shown to have no particular significance from a recovery standpoint. Before this rate can be used as a basis of comparison for recoveries, it is necessary that the relative permeability and capillary pressure characteristics and displacing fluid viscosities be identical for the systems compared.

A method is presented by which accurate prediction of the performance of a gravity drainage system can be made. Close agreement between experimental and calculated drainage performance shows that steady state relative permeability and static capillary pressure data can be used to describe fluid displacement behavior. The very wide range of liquid recoveries before gas breakthrough which result from production rate variation alone demonstrates the importance of this factor in planning depletion of a gravity drainage reservoir. Calculated results are presented which show that little additional recovery can be expected from a high pressure gravity drainage system between the times of gas breakthrough and attainment of such high gas/liquid ratios as to make further pressure maintenance impractical.

INTRODUCTION

It has been recognized for some time that gravity forces play an important part in the recovery of oil from some types of reservoirs. Field experience has shown that under certain conditions, gravity drainage can result in very high oil recoveries. Qualitative reasoning has led most engineers to the general conclusions that:

(1) Where gravity drainage is important, the reservoir pressure should be maintained by gas injection at the crest of the structure to prevent shrinkage of the oil in place and to keep a low viscosity so the oil can drain at the fastest possible rate.

(2) Recovery by gravity drainage is rate sensitive.

A survey of the literature indicates that while considerable work has been done on the effects of gravity in oil production problems, no satisfactory method of calculating the performance of gravity drainage reservoirs has been reported.[1,2,3,4,5] In the absence of any proven method of calculating reservoir performance, the level at which pressure should be maintained and the rate of production for most efficient operation has been open to debate.

The limits and general character of the recovery *vs* rate relationships are apparent from the following: As rates of production approach zero, oil will drain by virtue of its own weight fast enough that the saturation distribution is always approximately the same as the original static capillary distribution. That is, at the gas-oil contact the liquid saturation goes from 100 per cent to a value of perhaps 10 to 30 per cent in a very short distance, so that as production continues, a relatively sharp gas-oil contact moves down-structure, leaving a very low residual oil saturation in the originally oil saturated zone. At very high rates of production, the oil that drains by virtue of its own weight is negligible and recovery will approach that of a horizontal gas drive, leaving a much higher residual oil saturation. At intermediate rates of production, recovery should be between these extremes.

Despite the lack of quantitative methods, tentative agreement had been reached on the question of optimum producing rate. It has been generally concluded that rather sharp decrease in recovery would occur at rates of production above the "maximum rate of gravity drainage" and hence this rate should not be exceeded. The "maximum rate of gravity drainage" is defined as the rate of production from a 100 per cent

[1]References given at end of paper.

Manuscript received in the office of the Petroleum Branch Feb. 9, 1951. Paper presented at the AIME Annual Meeting in St. Louis, Mo., Feb. 17-22, 1951.

liquid-saturated system under a flow gradient equal to the gravity gradient or static pressure gradient differential between oil and gas due to density difference.

The purposes of the work reported herein were:

(1) To obtain accurate experimental data on performance of a gravity drainage system over a wide range of producing rates. This investigation covers only gravity drainage systems in which gas is injected at the crest of the structure to maintain pressure above the bubble point. Work is continuing on investigation of a system involving pressure decline during production by gravity drainage.

(2) To develop and thoroughly test a method whereby performance of a gravity drainage system at any producing rate may be calculated from laboratory data on the reservoir rock and its contained fluids.

APPARATUS AND PROCEDURE

Most fields are operated so that the oil production rate from the reservoir remains relatively constant over long periods of time. Production rate is a major factor affecting recovery and can be varied over a wide range for any one reservoir. One of the preliminary objectives of this investigation was to determine the effect of rate on recovery. Therefore, the equipment was designed so that liquid could be drained from a long unconsolidated sand column at various constant rates. A constant rate process was more easily described mathematically and could be analyzed more readily than one in which the rate varied continuously.

In order to obtain data for determining whether or not the results of the displacement process could be predicted accurately, it was necessary to measure saturation distributions at successive times in a system long enough to be free of boundary effects. These measurements had to be made without disturbing the flow of fluids by stopping the drainage or removing samples. Brine was used as the liquid phase since the saturations could be determined quickly and accurately by means of electrical conductivity measurements. There is no basic difference between displacement of oil or brine by gas. Performance will be governed by relative permeabilities, capillary pressure characteristics, differential densities, etc., which can be measured for either system.

Fig. 1 shows a schematic diagram of the flow system which was used in these experiments. The experimental flow system consisted of a two-in. ID Lucite tube, 13 ft long, packed with a clean silica sand which had the following size distribution:

U. S. Standard Sieve Size	Weight Per Cent
100-120	0.9
120-140	27.6
140-170	26.7
170-200	21.9
-200	22.9
	100.0

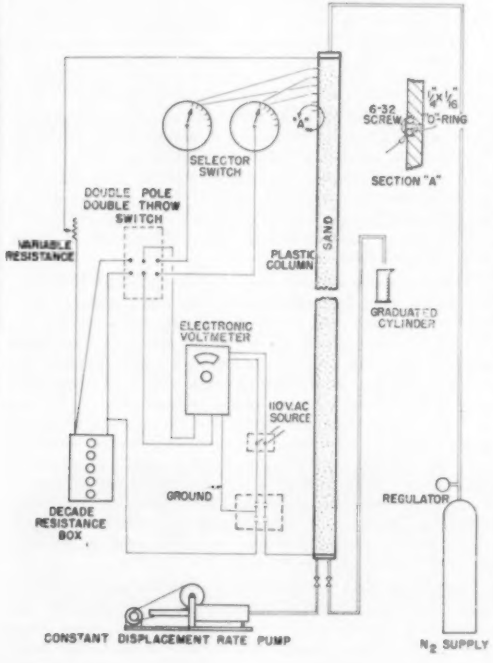

FIG. 1 — SCHEMATIC DIAGRAM OF APPARATUS.

The column was packed with sand by standing it in a vertical position and vibrating it horizontally at the sand level while the sand drained out of a one-half in. tube at the sand surface. This packing procedure was tested for a short column in order to determine the optimum conditions of packing. It was found that a minimum porosity of 33 per cent could be obtained when an amplitude of .003 to .005 in. and a frequency of 2,000 to 4,000 vibrations per minute were used. These tests also showed that no decrease in porosity could be obtained by filling the column at rates less than one in. per minute, so this speed was used for all packing. The column used in these tests had a brine permeability of 2.7 darcys. All of the other columns which were packed in this manner with the same size sand had very nearly the same permeability and porosity.

Early tests conducted on these sand-packed columns indicated an excessive amount of flow of fluids between the outside sand grains and the wall of the tubing. It was possible that this by-passing could seriously affect the results of displacement tests. In order to eliminate this boundary flow, the Lucite was heated until it became very plastic (about 270°F) and was then forced against the sand with an external pressure of 500 psi. This caused the Lucite to conform to the outside surface of the sand grains, but it did not become fluid enough to penetrate the sand. When the system was allowed to cool, the Lucite contracted around the sand until it was under considerable tension, which permitted the use of internal pressures up to the bursting strength of the Lucite before any by-passing occurred between the sand and the Lucite.

A method similar to that described by Wyckoff and Botset[6] was used for measuring electrical conductivity in order to

CHANGE IN SATURATION DISTRIBUTION WITH TIME

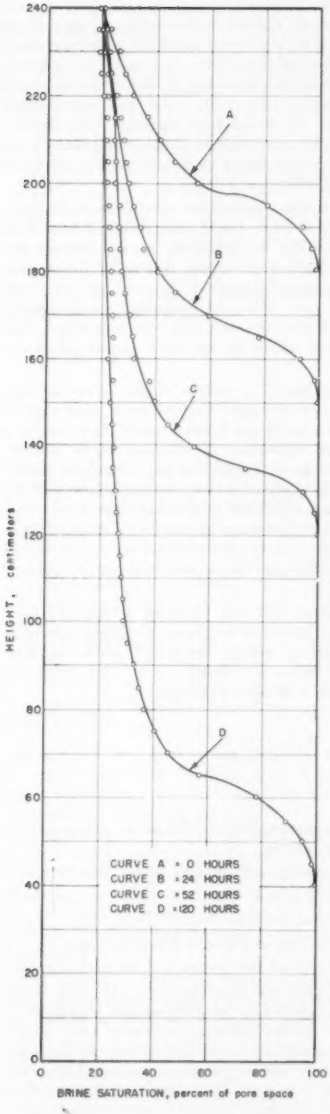

FIG. 2 — RATE OF 0.101 CU CM/MIN OR 2.6 PER CENT OF GRAVITY DRAINAGE REFERENCE RATE.

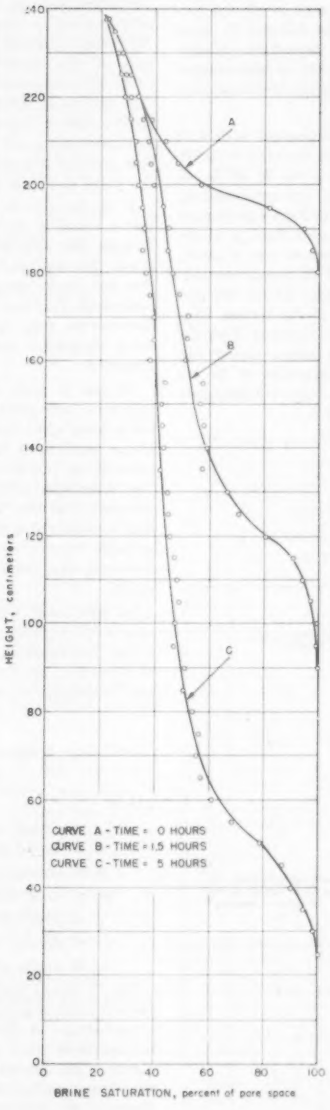
HEIGHT, centimeters
BRINE SATURATION, percent of pore space
A
B
C
CURVE A - TIME = 0 HOURS
CURVE B - TIME = 1.5 HOURS
CURVE C - TIME = 5 HOURS

FIG. 3 — RATE OF 1.538 CU CM/MIN OR 40.4 PER CENT OF GRAVITY DRAINAGE REFERENCE RATE.

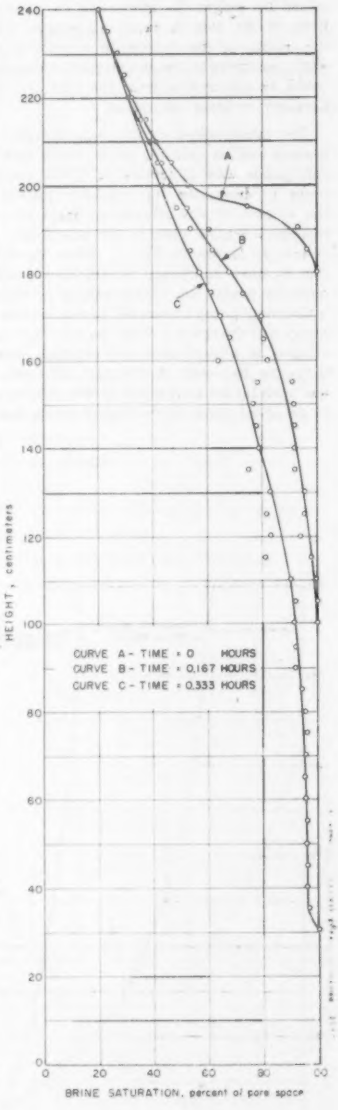
HEIGHT, centimeters
BRINE SATURATION, percent of pore space
A
B
C
CURVE A - TIME = 0 HOURS
CURVE B - TIME = 0.167 HOURS
CURVE C - TIME = 0.333 HOURS

FIG. 4 — RATE OF 8.60 CU CM/MIN OR 226 PER CENT OF GRAVITY DRAINAGE REFERENCE RATE.

determine saturation distributions in the column. Electrical contact was made at five-cm intervals by tapping a small screw through the wall of the Lucite tubing as shown in the insert in Fig. 1. A calibration curve was determined on a short length of sand-packed tube by measuring the electrical conductivity and comparing it to the brine saturation as determined by weight. By measuring the resistance of all the sections in the core in rapid succession (two minutes to scale the section of the column in which rapid saturation changes were occurring), the saturation distribution of the column could be determined from the plot of relative electrical conductivity *vs* brine saturation.

The sand-packed column was initially saturated with 0.25 normal sodium chloride brine which had a viscosity of 0.826 centipoises and a density of 1.006 gm/cu cm at 30°C. In order to determine the capillary pressure characteristics of the column, it was allowed to drain to capillary equilibrium through a siphon open to the atmosphere near the top of the system as shown in Fig. 1. When equilibrium was reached, that is, when no change in saturation could be noted, the conductivity profile was measured and production started through a metering pump connected to the bottom of the system. This pump was designed so that liquid could be removed from the column at a predetermined constant rate which varied less than one per cent. A constant nitrogen pressure of 50 psi was maintained at the top of the column to prevent evolution of dissolved gas from the liquid during flow.

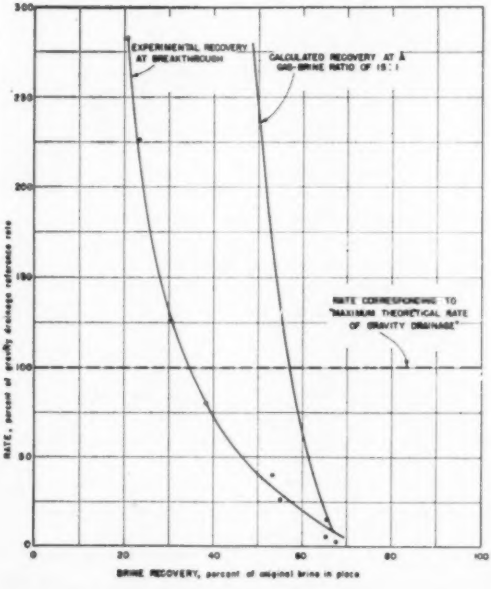

FIG. 5 — CHANGE IN RECOVERY WITH RATE.

DISCUSSION OF EXPERIMENTAL RESULTS

Figs. 2-4 show the saturation distribution at different times while liquid was being withdrawn from the 13-ft column at various constant rates. It can be seen for the low rate that above a certain liquid saturation, all saturation points move downward through the column at the same rate. Only a short time interval is required for this stabilization to take place. All points of liquid saturation less than those in the stabilized part of the saturation distribution curve move at different rates. The minimum liquid saturation at which this stabilization occurs is difficult to determine from the experimental curves and it cannot be determined directly from Darcy's Equation using relative permeability because capillary pressure and the ratio of gas to liquid viscosities have an effect on the point at which stabilization will occur.

It can be seen from these figures that the slope of the saturation curve is steep at high liquid saturations. It was first thought that this was due to by-passing which occurred between the sand and the Lucite tubing. It was for this reason that the Lucite was squeezed against the sand as previously described. However, even after the possibility of by-passing between the sand and the tube wall had been eliminated, this steep saturation curve above 95 per cent liquid saturation persisted.

As can be seen in Fig. 2, a portion of the saturation distribution curve maintains the same shape from a point high in the column until the time of gas breakthrough. This constant-shape portion of the saturation distribution curve will be referred to, for the sake of brevity, as the "stabilized zone." The remainder of the saturation distribution curve will be referred to as the "non-stabilized zone." Although it was possible to observe a stabilized zone at the lower rates of flow, at high rates it could not be determined whether a stabilized zone was formed because the column was not of sufficient length.

As previously pointed out, the yardstick which has been used as a criterion of efficiency in gravity drainage reservoirs is the "maximum rate of gravity drainage," or, as referred to here, the "gravity drainage reference rate." This reference rate is defined by the following equation:

$$GRR = \frac{K_L A}{\mu_L} g \Delta\rho \sin \alpha \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where

K_L = effective permeability to liquid at 100 per cent liquid saturation
A = cross-sectional area through which flow occurs
μ_L = viscosity of liquid
g = gravitational constant
$\Delta\rho$ = density difference between liquid and gas
α = angle of dip of the system (+ up and − down)

Fig. 5 shows the recovery obtained from the 13-ft sand-packed column as a function of production rate expressed as a percentage of the gravity drainage reference rate. It can be seen from these curves that no abrupt change in the slope occurs at the "maximum rate of gravity drainage." This reference rate contains only part of the factors which can affect recovery by gravity drainage, namely: permeability, area, viscosity of the oil, and pressure gradient due to the density difference between the gas and the oil. However, there are three important factors which are not included in this expression. It will be seen later that these three factors, capillary pressures, relative permeabilities, and displacing fluid viscosi-

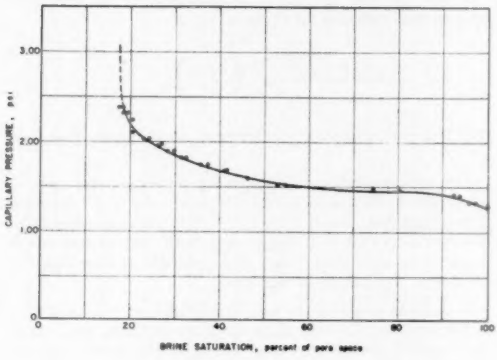

FIG. 6 — CAPILLARY PRESSURE CHARACTERISTICS OF 2.7 DARCY UNCONSOLIDATED SAND COLUMN.

ties, may be as important in determining the recovery by gravity drainage as any other of the factors contained in the gravity drainage reference rate. The gravity reference rate is sufficient to compare performance between systems in which the relative permeability, capillary pressure characteristics, and displacing fluid viscosities are the same. It is probable in field calculations where these three aforementioned factors are substantially equal for the entire field that it would be useful in comparing performance for different sections of the same reservoir. It should be kept in mind that when comparing performance between different fields or between model flow experiments and a field, differences in capillary pressure, displacing fluid viscosities, and relative permeabilities cannot be neglected.

Also shown in Fig. 5 is the calculated recovery to a formation gas/liquid ratio of 15:1. Experimental data following gas breakthrough were invalidated by capillary "end effect."[7] The ratio of 15:1 would be equivalent to a surface gas/liquid ratio in excess of 10,000 cu ft/bbl from a 2,000 psi reservoir if the liquid viscosity were 0.8 cp. This figure shows that at very low rates, little additional recovery can be obtained by producing the column to a 15:1 bbl/bbl ratio. However, as the rate was increased, the amount of additional recovery after gas breakthrough became a more important fraction of the total recovery.

Fig. 6 shows a static capillary pressure curve for the 13-ft sand-packed column. This curve was determined by allowing the column to drain as previously described.

Fig. 7 shows the relative permeability characteristics for the sand column. These curves were determined for a two-ft section which was packed in the same manner and with the same sand as that used in the 13-ft column. The short length was necessary so that equilibrium flow conditions could be established in a short length of time. For use in analysis of the experimental data, it was necessary to determine relative permeability characteristics with the same saturation history as prevailed during drainage of the column.[8] Therefore, the relative permeability data were measured starting with the sand section 100 per cent liquid saturated and decreasing the liquid saturation between subsequent measurements.

THEORY

Buckley and Leverett[9,10] presented Equations (2) and (3) to describe the behavior of two-phase fluid flow.

$$f_z = \frac{1 - \frac{K_L A}{Q_t \mu_o}\left[\frac{\partial P_c}{\partial S_g}\frac{\partial S_g}{\partial u} - g\Delta\rho \sin\alpha\right]}{1 + \frac{K_L}{K_g}\frac{\mu_g}{\mu_L}} \quad . \quad . \quad (2)$$

$$\left(\frac{\partial u}{\partial \theta}\right)_{S_g} = \frac{Q_t}{A\phi}\left(\frac{\partial f_g}{\partial S_g}\right)_\theta \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where,

f_z = fraction of gas flowing at any point
= gas flow rate/gas flow rate + liquid flow rate
K = effective permeability (darcys)
A = cross-sectional area of flow path (cm²)
ϕ = porosity (fraction)
u = length in the direction of flow (cm)
μ = viscosity (cp)
Q_t = total flow rate in the u direction (cu cm/sec)
P_c = capillary pressure (atms)
S = saturation to a particular phase (fraction)

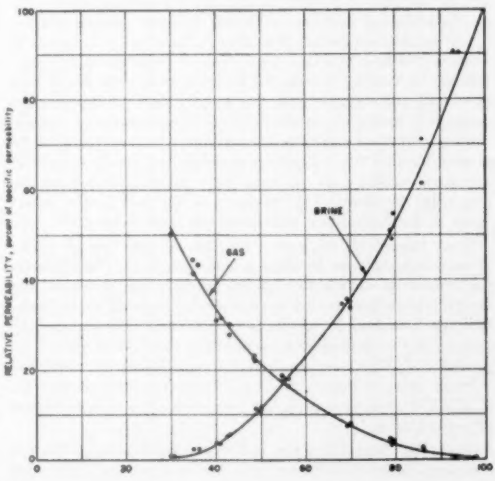

FIG. 7 — RELATIVE PERMEABILITY CHARACTERISTICS OF 2.7 DARCY UNCONSOLIDATED SAND COLUMN.

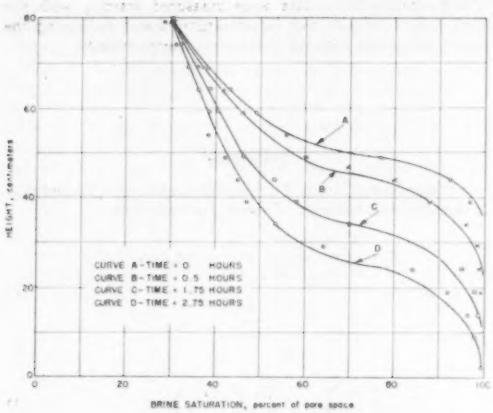
HEIGHT, centimeters
BRINE SATURATION, percent of pore space
CURVE A - TIME = 0 HOURS
CURVE B - TIME = 0.5 HOURS
CURVE C - TIME = 1.75 HOURS
CURVE D - TIME = 2.75 HOURS
A
B
C
D

FIG. 8 — COMPARISON OF CALCULATED AND EXPERIMENTAL SATURATION DISTRIBUTION DURING THE TRANSIENT PERIOD FOR A RATE OF 0.597 CU CM/MIN = 15.7 PER CENT OF GRAVITY DRAINAGE REFERENCE RATE (SOLID LINES REPRESENT CALCULATED DATA, POINTS THE EXPERIMENTAL RESULTS).

$g\Delta\rho$ = gravity gradient due to gas and liquid density difference (atms/cm)

α = angle of direction of u with the horizontal (measured + upward and − downward)

θ = time (sec)

$_g$ and $_l$ = (subscripts) denote gas and liquid, respectively

Equation (2) can be derived by combining Darcy's Equation for the rate of flow of wetting and non-wetting phase with the definition of capillary pressure. The only assumption involved in this equation is that Darcy's Law can be adapted to describe the flow in a two-phase system. Equation (3) can be derived by making a material balance on a differential unit of volume and requires only the assumption that the pressure gradient is negligibly small. While it is not necessary to their validity, practical application of these equations requires the assumption that static capillary pressure and steady state relative permeability data be applicable to the solution of displacement problems. This assumption, as well as the others made in the derivations, will be shown later to be valid.

If we know $(\partial f_g/\partial S_g)$ as a function of time for all points of saturation, we can, by the use of Equation (3), find directly the saturation distribution at any given time, provided that the saturation distribution is known at some other time. Therefore, the problem in solving for saturation distribution with time is that of finding this partial as a function of time. This partial $(\partial f_g/\partial S_g)$ can be found by graphical or numerical differentiation of Equation (2) if $(\partial S_g/\partial u)$ is known, since K_l, K_g and $(\partial P_c/\partial S_g)$ are each functions of S_g. Briefly, one method of doing this is:

A. At the time when the saturation distribution is known, it is possible by substituting $(\partial S_g/\partial u)$ in Equation (2) to solve for f_g at all points of saturation. This enables us to determine the slopes $(\partial f_g/\partial S_g)$ for all points of saturation at this time, θ_a.

B. We can then calculate the movement of all points of saturation by rearranging equation (3) to

$$(\Delta u)_{S_g} = \frac{Q_t\ \Delta\theta}{A\ \phi}\left(\frac{\partial f_g}{\partial S_g}\right)_{\theta_a}$$

and find the saturation distribution at the time $\theta_t = \theta_a + \Delta\theta$.

The approximation of substituting finite Δu and $\Delta\theta$ for infinitesimal changes in u and θ is valid only if $\Delta\theta$ for each step is kept very small when $(\partial f_g/\partial S_g)$ is changing rapidly. However, if $\Delta\theta$ for each step is kept small, and steps A and B repeated a great many times, it is possible to calculate the saturation distribution at any time.

In order to establish the validity of Equations (2) and (3), and the assumption that static capillary pressure and steady state relative permeability data are applicable to the solution of displacement problems, the above indicated calculations were performed for a flow rate of $Q_t = 0.597$ cu cm/min in the unconsolidated sand column, choosing $\theta = 0$ when capillary equilibrium had been established. The great number of steps involved, extreme sensitivity, and cumulative effect of small errors made solution by ordinary methods wholly impractical. Due to the repetitive nature of the calculation, it was handled very satisfactorily by use of punched card calculators. Presented in Fig. 8 is a graphical representation of the check obtained between the above method of calculation and the observed saturation distribution. The close agreement between experimental and calculated saturation distribution shows that, over the range of conditions investigated, Equa-

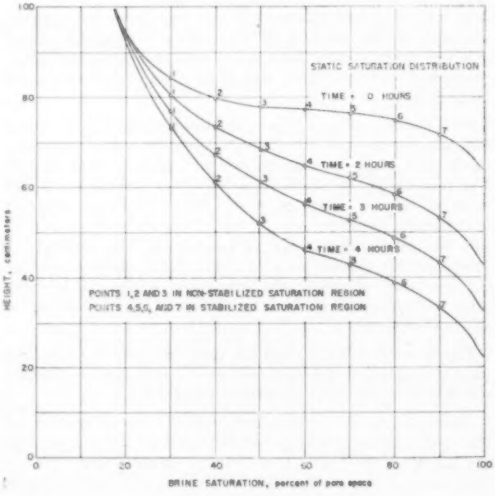
HEIGHT, centimeters
BRINE SATURATION, percent of pore space
STATIC SATURATION DISTRIBUTION
TIME = 0 HOURS
TIME = 2 HOURS
TIME = 3 HOURS
TIME = 4 HOURS
POINTS 1,2 AND 3 IN NON-STABILIZED SATURATION REGION
POINTS 4,5,6, AND 7 IN STABILIZED SATURATION REGION

FIG. 9 — VARIATION OF SATURATION DISTRIBUTION WITH TIME IN AN IDEALIZED SYSTEM.

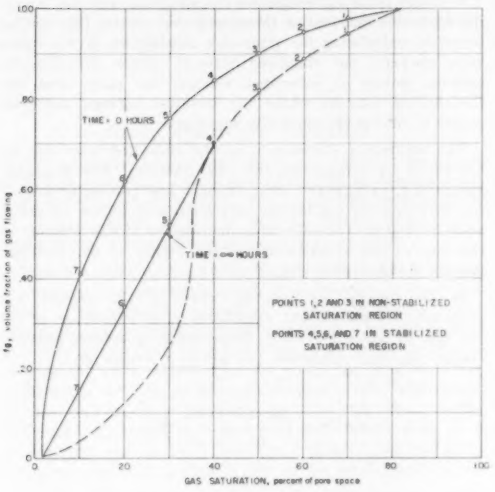
TIME = 0 HOURS
TIME = ∞ HOURS
POINTS 1,2 AND 3 IN NON-STABILIZED SATURATION REGION
POINTS 4,5,6, AND 7 IN STABILIZED SATURATION REGION
f_g, volume fraction of gas flowing
GAS SATURATION, percent of pore space

FIG. 10 — VARIATION OF f_g WITH TIME IN AN IDEALIZED SYSTEM.

tions (2) and (3) are valid, and also that transient flow problems can be solved by the use of static capillary pressure and steady state relative permeability data.

While it is possible by the type calculations indicated above to describe flow behavior in a system at any time, the cost of these calculations prevents this approach to the solution of routine reservoir engineering problems; therefore, a short cut method of solution was developed.

As previously mentioned, it has been observed in the 13-ft laboratory core that at some rates of flow a stabilized zone is formed; that is, all points of saturation in this region move down the column at the same rate and therefore the shape of this portion of the saturation distribution curve becomes constant with time. All points of gas saturation greater than those in the stabilized zone move at different rates. Fig. 9 schematically describes drainage from a column. In Fig. 9 point 1 always moves slower than point 2, and point 2 slower than point 3, and so on until the stabilized zone is reached when points 4 and 5 and all other points of lower gas saturation move at the same rate. This means that $(\partial f_g/\partial S_g)$ used in Equation (3), which is directly proportional to rate of movement of a point of saturation, is smaller for point 1 than it is for point 2, than it is for point 3, etc., until points 4 and 5 and points of lower gas saturation are reached, at which time it becomes constant. Because $(\partial f_g/\partial S_g)$ is the slope of the f_g *vs* S_g curve, we can (from the above experimental observations) conclude what the shape of the curve must be. It means that if we start at a point of high gas saturation, illustrated by point 1 on Fig. 10 and proceed toward a region of lower gas saturation, the curve must be ever-steepening $[(\partial f_g/\partial S_g)$ increasing] until the stabilized zone, represented by points 4 and 5, is reached, at which time it becomes a straight line. In other words, the stabilized zone moves as a unit, always keeping the same shape and the remaining part stretches until $(\partial S_g/\partial u)$ approaches 0. This means that, as a limiting case, the behavior of the non-stabilized zone can be found by setting $(\partial P_c/\partial S_g)\ (\partial S_g/\partial u) = 0$.

Then

$$f_g = \frac{1 - \dfrac{K_L\ A}{Q_t\ \mu_L}\ [\ -g\Delta\rho\ \sin\ \alpha\ ]}{1 + \dfrac{K_L}{K_g}\ \dfrac{\mu_g}{\mu_L}} \qquad \ldots\ldots\ (4)$$

The dotted curve on Fig. 10 indicates the kind of curve given by this equation.

Now, since the slope of the f_g *vs* S_g curve must be ever increasing or remain constant as we go from a point of high gas saturation toward points of lower gas saturation, the f_g *vs* S_g curve will, as a limit, very closely approach the curve constructed by starting at the highest possible gas saturation (1 – irreducible liquid saturation) and following along the curve

$$f_g = \frac{1 - \dfrac{K_L\ A}{Q_t\ \mu_L}\ [\ -g\Delta\rho\ \sin\ \alpha\ ]}{1 + \dfrac{K_L}{K_g}\ \dfrac{\mu_g}{\mu_L}}$$

to a point where a tangent to this curve will pass through the equilibrium gas saturation at $f_g = 0$. In a strict sense, the f_g *vs* S_g curve will equal the above-described curve only at the time θ = infinity; but for practical purposes this curve is

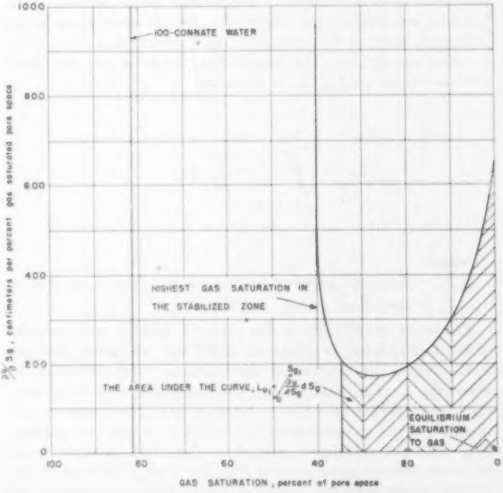
100-CONNATE WATER
HIGHEST GAS SATURATION IN THE STABILIZED ZONE
THE AREA UNDER THE CURVE, $L_u = \int_{S_{g_1}}^{S_{g_2}} \frac{\partial S_g}{\partial f_g} dS_g$
EQUILIBRIUM SATURATION TO GAS
$\partial S_g/\partial f_g$, centimeters per percent gas saturated pore space
GAS SATURATION, percent of pore space

FIG. 11 — CALCULATION OF THE LENGTH OF THE STABILIZED ZONE, L_u.

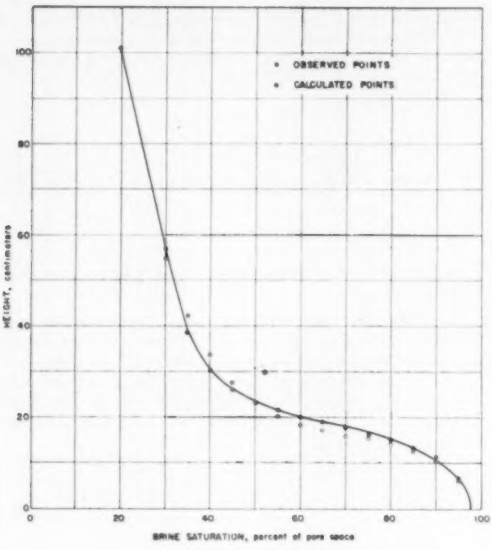

FIG. 12 — COMPARISON OF CALCULATED AND EXPERIMENTAL SATURATION DISTRIBUTION AFTER A STABILIZED ZONE HAS FORMED AT A RATE OF 0.101 CU CM/MIN = 2.6 PER CENT GRAVITY DRAINAGE REFERENCE RATE.

approached rapidly. Once the f_g *vs* S_g curve is known, after a stabilized zone is formed its length and shape can be calculated by substituting the values of f_g for all saturations in the stabilized zone in Equation (2) and solving for the $\partial S_g/\partial u$ at these saturations. The length and shape of this stabilized zone as shown on Fig. 11 is given by

$$L_u = \int_{S_g=0}^{S_g} \frac{\partial u}{\partial S_g}\, dS_g \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where

L_u = distance, in the u direction (cm) from $S_g = 0$ to S_g

S_g = saturation to gas (fraction)

Presented graphically in Figs. 12, 13, and 14, are comparisons of calculated *vs* observed stabilized saturation distributions. Since the calculated distributions were obtained by assuming f_g *vs* S_g relationship corresponding to θ = infinity, the close agreement existing between calculated and experimental results demonstrates the validity of this assumption. The observed stabilized saturation distributions were found by averaging the experimental data for several different times. It was noted that the variation between the calculated and observed saturation distributions at different times was less than the random variation in observed distributions at different times.

Recovery to breakthrough can be calculated once one knows the saturation distribution throughout the system. This can be found by calculating the saturation distribution in two intervals; namely, the stabilized interval where the distance between points of saturation remains the same, and the unstabilized interval where the distance between any two points of saturation constantly increases.

The saturation distribution in the stabilized zone can be calculated by substituting into the fractional flow equation, values of f_g *vs* S_g read from a straight line portion of a f_g *vs* S_g curve and solving for the saturation distribution as previously indicated. The saturation distribution in this interval at the time of gas breakthrough at the bottom of the drainage column is indicated in Fig. 15.

In the unstabilized interval, where $\partial P_c/\partial u$ rapidly approaches 0, Equation (4) establishes f_g as a function of S_g. We can, by plotting f_g *vs* S_g, determine by graphical differentiation $(\partial f_g/\partial S_g)$. Equation (3) can be rewritten as

$$(\Delta u)S_g = \frac{Q_t\ \Delta\theta}{A\phi}\left(\frac{\partial f_g}{\partial S_g}\right)$$

which will relate the total movement of each point of saturation with $(\partial f_g/\partial S_g)$. $Q_t\Delta\theta/A\phi$ is the same for all saturations; therefore, the movement of each point of saturation is directly proportional to $(\partial f_g/\partial S_g)$. The saturation distribution in this interval can then be calculated if we can find $Q_t\Delta\theta/A\phi$. The (Δu) for the lowest point of S_g which does not stabilize can be found by subtracting the length of the stabilized zone from the total length of the system as indicated in Fig. 15. Then $Q_t\Delta\theta/A\phi$ can be found because we know both Δu and $(\partial f_g/\partial S_g)$ for this saturation. The Δu's for each other point of saturation in this interval are calculated by multiplying this number $(Q_t\Delta\theta/A\phi)$ by the appropriate $(\partial f_g/\partial S_g)$. Indicated also in Fig. 15 is the kind of saturation distribution that is calculated by this means. After the saturation distribution for both saturation intervals is known, the average saturation can be obtained and hence the recovery to breakthrough. Presented in Table I is a comparison of calculated and observed recovery from the 13-ft unconslidated sand column. The recoveries calculated were for low rates of withdrawal only. At higher rates stabilized zones did not develop for the reason that the experimental column was of shorter length than the stabilized zone length would have been. However, there is no reason to believe that the indicated method of calculation

Table I

Rate Per Cent of GRR	Experimental Recovery Per Cent of Brine in Place	Calculated Recovery Per Cent of Brine in Place
2.7	67.9	68.0
5.7	65.8	66.4
15.7	64.2	65.5
26.3	56.4	59.9
40.5	53.3	53.4
80.8	39.1	
126	30.8	
226	22.4	
283	20.7	

would not give the same good agreement for all rates in a system long enough to allow the formation of stabilized zones before gas breakthrough.

DISCUSSION OF THEORY

The agreement between calculated and observed recoveries in Table I shows that this method of calculation permits accurate calculation of performance of a linear homogeneous gravity drainage system by use of fluid and rock characteristics which can be measured separately in the laboratory.

With the method of calculating recovery from a gravity drainage system developed above, it is possible to study the effects of the variables controlling recovery by gravity drainage. As shown previously, recovery varies in a smooth fashion with rate and no sharp change occurs at the gravity reference rate. In the 13-ft column used for study, the lengths of the stabilized zones were an appreciable part of the total length of the system, thus variations in stabilized zone lengths markedly influenced the recovery *vs* rate relationship. In a system long enough such that the length of the stabilized zones represented a negligible part of the total length of the system, recovery *vs* rate relationships should be expected to be considerably different. Fig. 16 shows a comparison of the recovery that would be obtained from a 1,000-ft column with fluid and rock characteristics identical to those of the 13-ft system. Here, neither, is there any extreme change in recovery at the gravity reference rate, but the rate of increase in recovery as withdrawal rates are lowered is essentially constant over all rates of production and recovery for every rate is somewhat higher than for the 13-ft column. In the 1,000-ft system, changes in recovery are caused only by differences in the recovery from the non-stabilized zone, since the length of the stabilized zone is negligible in comparison to the length of the total system.

Shown also in Fig. 16 are curves indicating the recovery that would be obtained from the 1,000-ft system by production at constant pressure after gas breakthrough to 15:1 formation gas/liquid ratio. In calculating these curves, two extremes of production rate were assumed. In one case the total flow rate, that is, the gas plus liquid, was held constant after breakthrough. It is doubtful whether a field could be operated in this manner due to the rapid decrease in liquid production as the gas/liquid ratio increases. To illustrate the other extreme in performance, calculations were made to determine what recovery would result if a 1,000-ft column

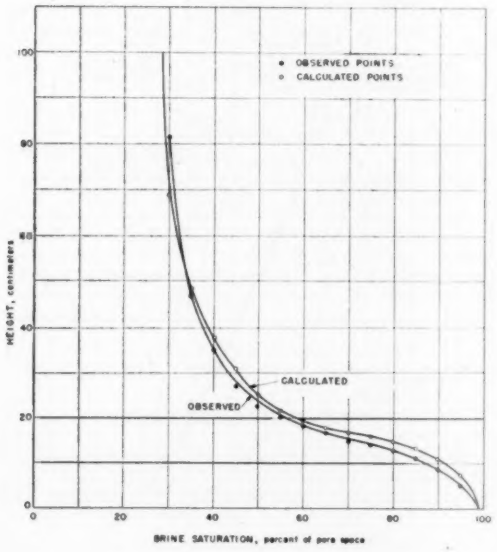

FIG. 13 — COMPARISON OF CALCULATED AND EXPERIMENTAL SATURATION DISTRIBUTION AFTER A STABILIZED ZONE HAS FORMED AT A RATE OF 0.215 CU CM/MIN = 5.5 PER CENT OF GRAVITY DRAINAGE REFERENCE RATE.

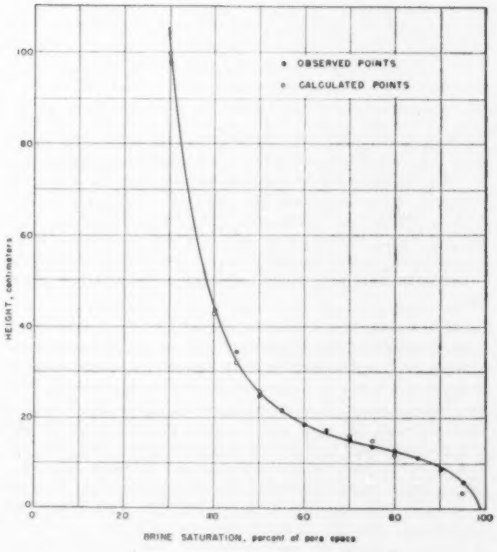

FIG. 14 — COMPARISON OF CALCULATED AND EXPERIMENTAL SATURATION DISTRIBUTION AFTER A STABILIZED ZONE HAS FORMED AT A RATE OF 0.597 CU CM/MIN = 15.7 PER CENT OF GRAVITY DRAINAGE REFERENCE RATE.

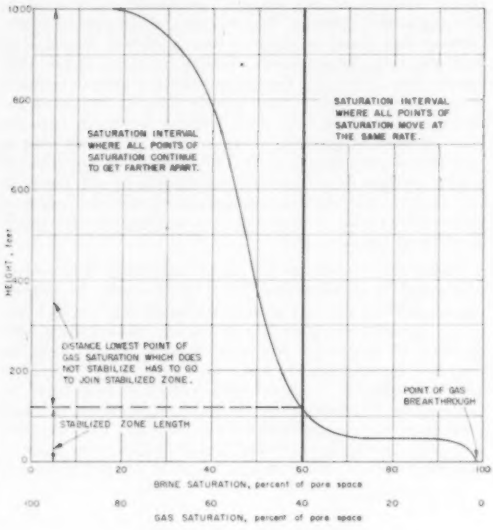
SATURATION INTERVAL WHERE ALL POINTS OF SATURATION CONTINUE TO GET FARTHER APART.
SATURATION INTERVAL WHERE ALL POINTS OF SATURATION MOVE AT THE SAME RATE.
DISTANCE LOWEST POINT OF GAS SATURATION WHICH DOES NOT STABILIZE HAS TO GO TO JOIN STABILIZED ZONE.
POINT OF GAS BREAKTHROUGH
STABILIZED ZONE LENGTH
HEIGHT, feet
BRINE SATURATION, percent of pore space
GAS SATURATION, percent of pore space

FIG. 15 — EXAMPLE OF SATURATION DISTRIBUTION CALCULATIONS AT GAS BREAKTHROUGH.

at the gravity reference rate differ by approximately one-third of the recovery. It can be seen similarly that large differences in recovery at a given rate can be caused by differences in relative permeabilities between different systems. Hence, it is obvious that before recoveries between fields can be compared, it is necessary that the relative permeability characteristics, the viscosity ratio (viscosity of gas divided by viscosity of oil), as well as rate expressed as a fraction of the gravity reference rate be comparable.

When applying the method of calculation presented in this paper to field studies, appropriate adjustments must be made for the variations in physical properties between various parts of the reservoir that are always present in oil fields. Commonly accepted engineering practices can be followed in dividing the reservoir into more or less homogeneous blocks or else arriving at average characteristics for the field as a whole. The effects of stratification and gas coning, of course, will modify the idealized situations considered here. Whether production is taken from wells distributed throughout the completely liquid saturated zone rather than the lowest structural portion will in no way affect the regional liquid displacement picture, except for local coning effects. If oil is withdrawn only from the completely liquid saturated zone, the recovery when gas breaks through into the lowest wells will

were produced after gas breakthrough at a constant liquid rate. The calculated recoveries to a formation gas-liquid ratio of 15:1 for this case are also plotted on Fig. 16. From this curve, it can be seen that, for most rates, the recovery to a high produced gas/liquid ratio after breakthrough is negligible if liquid production is held constant. Most fields would be produced at rates intermediate between these two extremes — constant total rate (liquid and gas) and constant liquid rate.

Since in practice a constant liquid rate is maintained as long as possible, liquid recovery will be small between the time of gas breakthrough and the time when further pressure maintenance becomes uneconomical due to prohibitively high gas/liquid ratios. In some fields where crude and formation characteristics are such that economical rates of production can be maintained at a low reservoir pressure, it may be feasible to cycle gas after the pressure has declined. In such a case, a much higher formation gas/liquid ratio than 15:1 can be economically handled by a cycling plant and correspondingly larger recovery obtained after breakthrough. Of course, if pressure cannot be maintained, the liquid saturation will be reduced markedly by oil shrinkage alone.

Fig. 17 shows the effect of displacing fluid viscosity on recovery variations with rate from a 13-ft unconsolidated sand column. This figure shows calculated recoveries *vs* rate for brine being displaced by two displacing fluids of different viscosities. Here again no marked change in recovery is observed at the gravity reference rate. Moreover, recoveries

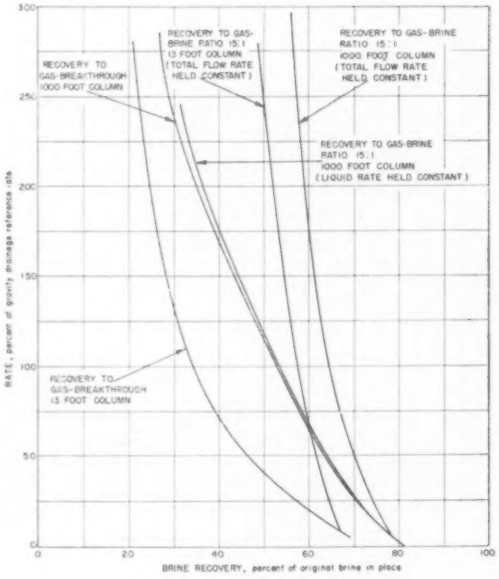
RECOVERY TO GAS-BREAKTHROUGH 1000 FOOT COLUMN
RECOVERY TO GAS-BRINE RATIO 15:1 13 FOOT COLUMN (TOTAL FLOW RATE HELD CONSTANT)
RECOVERY TO GAS-BRINE RATIO 15:1 1000 FOOT COLUMN (TOTAL FLOW RATE HELD CONSTANT)
RECOVERY TO GAS-BRINE RATIO 15:1 1000 FOOT COLUMN (LIQUID RATE HELD CONSTANT)
RECOVERY TO GAS-BREAKTHROUGH 13 FOOT COLUMN
RATE, percent of gravity drainage reference rate
BRINE RECOVERY, percent of original brine in place

FIG. 16 — VARIATION OF RECOVERY WITH RATE FOR A 13-FT AND 1,000-FT SYSTEM AT GAS BREAKTHROUGH AND AT A 15:1 LIQUID/GAS RATIO.

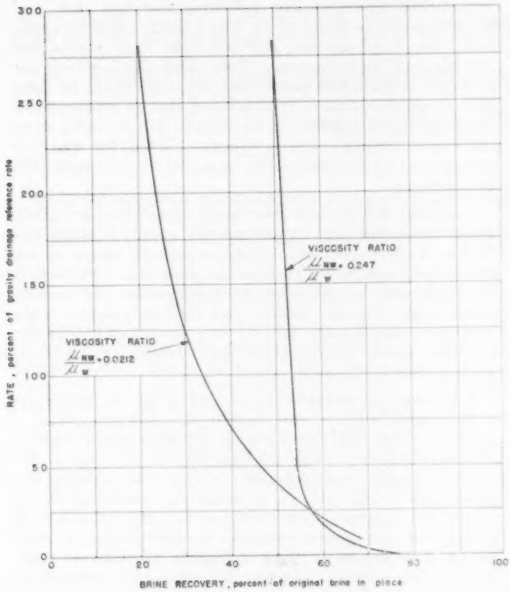

FIG. 17 — EFFECT OF VISCOSITY RATIO ON RECOVERY VARIATIONS WITH RATE IN A 13-FT UNCONSOLIDATED SAND COLUMN.

be that calculated for gas breakthrough in the idealized situations considered above.

The method indicated for determining gravity drainage performance is believed applicable, with appropriate modification, to the solution of all immiscible fluid displacement problems, such as updip water encroachment, horizontal gas and water drives, etc. Data to verify this are not now available, but experiments are planned to test the validity of this method of calculating the performance of immiscible fluid displacement processes.

ACKNOWLEDGMENT

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★ ★ ★

DISCUSSION

By L. F. Elkins, Sohio Petroleum Co., Oklahoma City, Member AIME

The authors are to be commended for presentation of an excellent discussion of an experimental and theoretical investigation of effects of gravity drainage on efficiency of displacement of liquids from porous media.

It is heartening to see the development and solution of the analytical expressions of flow of mixtures of fluids in porous media keep pace with laboratory techniques, and it is particularly gratifying to see the excellent agreement between the experimental data for unsteady flow tests and the calculated saturation distribution based on relative permeability and capillary pressure data from other types of tests.

I should like to make one comment about the theoretical calculations that is minor from a practical viewpoint, at least for this particular sand-water-gas system, but is important from the viewpoint of mathematical sufficiency. This is with regard to the linear extrapolation of the f_g function to the equilibrium gas saturation at which $f_g = 0$ such as in Fig. 10. In my opinion this extrapolation of f_g *vs* S_g must be made to the zero gas saturation point and the relation must have a real derivative not equal to zero at that point. Otherwise velocities of points of gas saturations less than the equilibrium saturation are indeterminant. Physically the first point of zero gas saturation occurs with a curved gas/liquid interface moving through a pore and, under these conditions, the relative permeability-saturation concept is meaningless since all factors such as saturation, flow rates, etc., are statistical averages over many pores.

The second comment I should like to make has to do with the numerous references to the lack of significance of a "maximum rate of gravity drainage." As used in this paper the "gravity drainage reference rate" does have no significance with regard to recoveries, gas/oil ratios, etc. However, its definition herein is not the same as that included in our papers a few years ago in which a simplified method of estimating rates of regional migration by gravity drainage was introduced. In this paper the "gravity drainage reference rate" was calculated using effective permeability to liquid at 100 per cent liquid saturation. In our paper no saturation was specified and the effective permeability was presumed to vary as reservoir conditions changed. Thus it includes effects of relative permeability which are of great importance. These must be determined from laboratory tests and comparison

with other fields. Our paper then proceeded to show how the effective permeability to oil and gravity drainage rate had declined at Lance Creek.

It is unfortunate that we failed properly to convey our concept of the mechanism of gravity drainage and the mathematical evaluation thereof to these authors and other readers. Field experience and their laboratory experiments both have shown that oil recovery efficiency expressed in terms of gas/oil ratio performance is very sensitive to production rate. It will be through extensions of the type of calculations presented in this paper plus analogy with performance of other oil reservoirs that our understanding of gravity drainage will be increased and the accuracy of our predictions involving particular reservoir problems improved.

AUTHORS' REPLY TO MR. ELKINS

In regard to extrapolations of the f_g function to the equilibrium gas saturation at which f_g is zero, we believe the equilibrium gas saturation is very nearly zero. As can be seen from Figs. 2, 3 and 4, the equilibrium gas saturation reaches very low values (one-half of one per cent). In all of the experiments considerable distance is required for the gas saturation to reach a value which is usually referred to as the equilibrium saturation, that is, 5 to 15 per cent.

The existence of a low equilibrium gas saturation is also substantiated by the fact that carefully measured capillary pressure curves always show a finite slope at very low saturations to gas.

DISCUSSION

By E. R. Brownscombe, The Atlantic Refining Co., Dallas, Tex., Member AIME

The authors have made a very significant contribution in extending our interpretation of displacement problems. The Leverett and Buckley analysis has been the foundation of the calculation of reservoir performance from relative permeability data. As generally practiced, the saturation distribution behind the front is calculated and the position of the front determined from material balance dictates, the saturation being arbitrarily cut to zero at this point. The present paper gives a method for calculating the shape of the front in terms of capillary pressure and gravitation effects. It shows how the shape of the front is affected by factors such as rate of displacement and viscosity ratio of the fluids. In an actual reservoir, since the length of the zone which might be referred to as a front is generally very small compared to overall distances in the reservoir, this analysis probably will not have any appreciable effect on the calculation of the general sweep of a displacing fluid through a reservoir. It may be useful in estimating the effect of small scale variations in the reservoir. It will be very important in interpreting the results of laboratory experiments on small cores. For example, we have reproducible laboratory data indicating that high rates lead to increased recoveries, others that indicate that low rates lead to increased recovery, and still others that indicate that rate has no effect on recovery. These same startling facts can be found in published data in the literature based on flood tests of small specimens. It is believed that an interpretation along the lines suggested by the authors will reconcile these differences. Probably most conclusions about the effect of rate on recovery obtained to date on small cores are practically meaningless.

It is noted that the authors mention a small pressure gradient as being the only requirement for a valid Leverett and Buckley analysis. Actually, it may be perfectly proper to use the analysis even when the pressure gradient is very high, if the fluids used are essentially incompressible. The requirements implicit in the Leverett and Buckley analysis might perhaps be better given as: (1) very small density changes in either phase, (2) small viscosity changes, and (3) no material transfer between phases.

The numerical computation referred to by the authors is of particular interest. This method of calculation offers a powerful tool for the solution of partial differential equations. Engineers concerned with the developments of methods for reservoir analysis are constantly running into problems too difficult to handle with the conventional mathematical approach. The numerical computing approach offers considerable promise for solving these problems. To date practically nothing has been published which is directly applicable to problems of this sort. I would like to suggest that the authors publish the details of the numerical computation. It would be very helpful to know, for example, what the effect of variation of the size of the time intervals was and whether there appeared to be any critical ratio of the size of the time interval to the size of the distance interval.

AUTHORS' REPLY TO MR. BROWNSCOMBE

There have been no experiments conducted in which there was an original gas saturation throughout the column. The main reason such experiments have not been attempted is that it is difficult rapidly to obtain equilibrium between oil and gas in a porous system. When pressure is lowered on a sand column containing liquid with dissolved gas, the two phases will not come to equilibrium immediately and the performance of the system is partially controlled by the rate at which gas came out of solution.

It is possible that the presence of connate water will have some effect on the capillary pressure curve. However, when these calculations are made for an oil reservoir, they should be based on a capillary pressure curve determined by displacing oil from a core by gas. In order to be sure that the correct capillary pressure curve will be obtained, the core should contain connate water.

At the time this paper was first presented, no experiments had been conducted in which water was used to displace a non-wetting fluid. Since that time, however, several experiments have been conducted in which oil was displaced by updip water flood, and performance of this displacement process computed by use of imbibition relative permeability and capillary pressure curves. The data obtained indicate that this method of computation is satisfactory for predicting the performance of water drives. ★ ★ ★

PHASE EQUILIBRIA IN HYDROCARBON-WATER SYSTEMS

IV - Vapor-Liquid Equilibrium Constants in the Methane-Water and Ethane-Water Systems

O. L. CULBERSON, GULF RESEARCH AND DEVELOPMENT CO., HARMARVILLE, PA., AND J. J. McKETTA, JR., MEMBER AIME, DEPARTMENT OF CHEMICAL ENGINEERING, THE UNIVERSITY OF TEXAS, AUSTIN, TEX.

INTRODUCTION

The equilibrium constants for methane and for water, and for ethane and water have been calculated from experimental data for the two binary systems.[2,9,11,12] These constants are for the two-phase systems for the temperature range of 100° to 340°F and the pressure range of 200 to 10,000 psia.

The constants for ethane are greater than those for methane. Equilibrium constants for a natural gas from a natural gas-water system[6] are about the same as those for methane. Equilibrium constants for water in all three systems are very nearly the same over the greater part of the range of temperatures and pressures studied.

In ideal solutions, the vapor-liquid equilibrium constants for a component should be the same in all such solutions at a given temperature and pressure.[5] Few solutions are ideal, and consequently the use of generalized constants often leads to error in situations where they do not actually apply. In decidedly non-ideal systems, it is desirable to have equilibrium constant data for the specific system.

Vaporization equilibrium constants may be calculated either by thermodynamic methods or from experimental vapor-liquid equilibrium data. In the thermodynamic calculation, the equilibrium constant K may be shown to be[10]

$$K = f_{Pi}/f_P \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where f_{Pi} is the fugacity of the pure component i at the given temperature and at the vapor pressure of the pure component, and f_P is the fugacity of pure i in the gaseous state at the temperature and total pressure of the system. At best the thermodynamic calculation results in a K applicable to ideal solutions. Equilibrium constants calculated from Equation (1) have been found to have only limited agreement with experimental values, even though the solutions for which they were calculated approached ideality.[8,9] If the more volatile component is at a temperature above its critical, the accuracy of the equilibrium constant for the component is made more doubtful by the use of the vapor pressure term under such conditions. In order to make the thermodynamic calculation on a component above its critical temperature, one must resort to one of the empirical methods of extrapolation of the vapor pressure to conditions above its critical point.[10] Application of the thermodynamic equilibrium constant then to the methane-water or the ethane-water systems would be risky since the systems are non-ideal, and the methane and ethane are above their critical in most petroleum operations.

ETHANE-WATER SYSTEM

In the temperature range of from 100° to 340°F and for pressures up to 10,000 psia, the vapor-liquid equilibrium data

[2]References given at end of paper.

Manuscript received in the office of the Petroleum Branch March 16, 1951.

Table I — Vaporization Equilibrium Constants for Ethane in the Ethane-Water System

Pressure psia	100°F	160°F	220°F	280°F	340°F
200	3,034	5,639	6,335	4,962	3,678
400	1,868	2,837	3,194	2,557	1,882
600	1,496	2,074	2,159	1,729	1,280
800	1,333	1,746	1,747	1,339	1,001
1,000	1,260	1,583	1,515	1,146	838
1,250	1,215	1,457	1,326	993	723
1,500	1,177	1,366	1,198	898	652
2,000	1,125	1,265	1,035	789	554
2,500	1,092	1,200	971	726	489
3,000	1,071	1,142	924	679	445
3,500	1,042	1,093	885	645	416
4,000	1,018	1,049	854	620	396
4,500	990	1,012	833	599	384
5,000	968	984	813	579	374
6,000	925	941	772	550	354
7,000	899	909	736	528	337
8,000	888	874	704	511	322
9,000	885	841	679	494	308
10,000	882	813	663	479	295

Table II — Vaporization Equilibrium Constants for Water in the Ethane-Water System

Pressure psia	$K \times 10^3$ 100°F	160°F	220°F	280°F	340°F
200	5.009	24.49	87.83	250.7	595.5
400	2.642	12.69	45.08	127.9	303.7
600	1.860	8.783	30.80	86.98	206.6
800	1.475	6.837	23.73	66.66	153.2
1,000	1.245	5.679	19.52	54.51	129.2
1,250	1.066	4.755	16.17	44.91	106.3
1,500	0.950	4.150	13.97	38.45	90.60
2,000	0.813	3.412	11.22	30.55	71.81
2,500	0.735	2,981	9.620	25.81	60.54
3,000	0.689	2.711	8.562	22.75	53.33
3,500	0.659	2.523	7.836	20.56	48.16
4,000	0.641	2.392	7.308	19.08	44.36
4,500	0.627	2,294	6.913	17.94	41.48
5,000	0.621	2.220	6.611	17.04	39.16
6,000	0.618	2.120	6.181	15.73	35.70
7,000	0.620	2.070	5.898	14.78	33.28
8,000	0.624	2.032	5.658	13.99	31.26
9,000	0.627	1.995	5.439	13.35	29.53
10,000	0.630	1.954	5.215	12.77	28.04

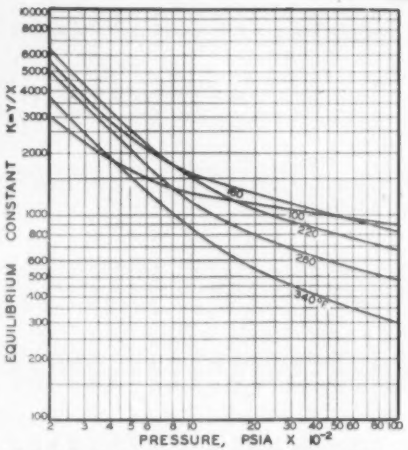


FIG. 1—EQUILIBRIUM CONSTANTS FOR ETHANE IN ETHANE-WATER SYSTEM (*K-P*).

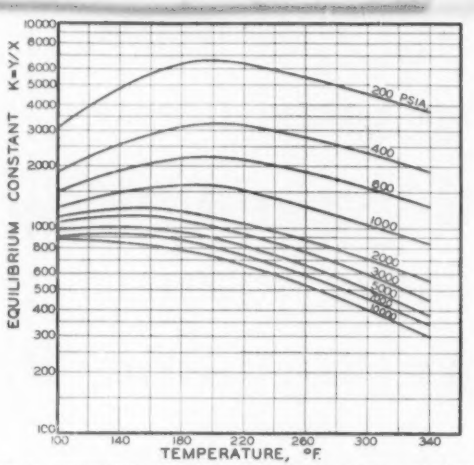


FIG. 2 — EQUILIBRIUM CONSTANTS FOR ETHANE IN ETHANE-WATER SYSTEM (*K-T*).

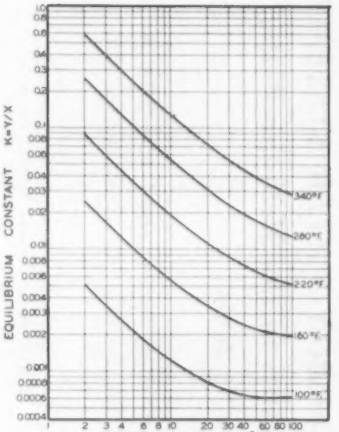


FIG. 3 — EQUILIBRIUM CONSTANTS FOR WATER IN ETHANE-WATER SYSTEM (*K-P*).

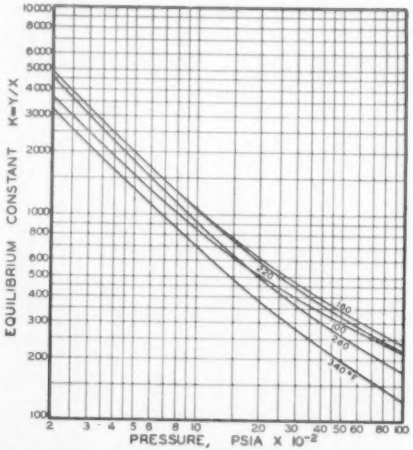


FIG. 4—EQUILIBRIUM CONSTANTS FOR METHANE IN METHANE-WATER SYSTEM (*K-P*).

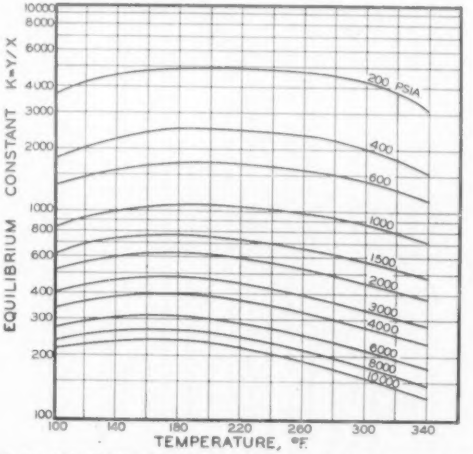


FIG. 5 — EQUILIBRIUM CONSTANTS FOR METHANE IN METHANE-WATER SYSTEM (*K-T*).

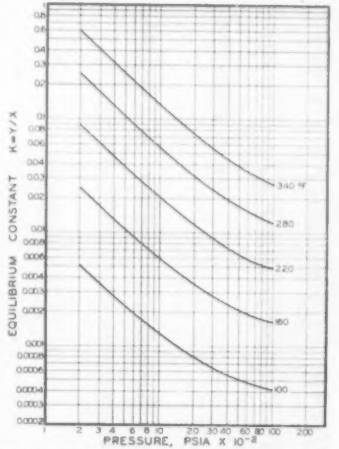


FIG. 6 — EQUILIBRIUM CONSTANTS FOR WATER IN METHANE-WATER SYSTEM (*K-P*).

Table III — Experimental Determinations of Vapor Phase Composition in the Ethane-Water System at 100°F

Pressure psia	Mole Fraction H_2O x 10^3 Experimental	Literature Smoothed[2]	Experimental % Deviation
608	2.090	1.830	+ 14.2
629	1.836	1.790	+ 2.57
655	1.638	1.733	- 5.48
718	1.726	1.605	+ 7.54
728	1.195	1.570	- 23.9
1,745	0.919	0.910	+ 1.00
		Average Deviation	9.11%

Table IV — Vaporization Equilibrium Constants for Methane in Methane-Water System

Pressure psia	100°F	160°F	220°F	280°F	340°F
200	3,644	4,804	4,847	4,537	3,080
400	1,889	2,425	2,491	2,244	1,620
600	1,313	1,654	1,693	1,501	1,130
800	1,013	1,273	1,297	1,149	873
1,000	833	1,052	1,054	929	705
1,250	701	878	856	750	568
1,500	617	761	736	631	478
2,000	512	620	595	489	377
2,500	445	536	505	413	318
3,000	399	476	444	365	280
3,500	365	432	400	328	252
4,000	337	397	368	299	230
5,000	297	346	321	258	198
6,000	270	310	288	231	176
7,000	251	284	265	210	159
8,000	236	264	247	195	145
9,000	224	249	232	181	134
10,000	214	237	219	171	126

Table V — Vaporization Equilibrium Constants for Water in Methane-Water System

Pressure psia	K x 10^3 100°F	160°F	220°F	280°F	340°F
200	5.089	24.85	88.79	251.47	596.61
400	2.709	13.02	45.95	129.33	306.96
600	1.914	9.010	31.64	88.70	210.39
800	1.515	7.082	24.49	68.33	161.68
1,000	1.277	5.894	20.20	56.25	132.57
1,250	7.086	4.948	16.78	46.43	109.40
1,500	0.956	4.308	14.47	39.82	93.72
2,000	0.796	3.510	11.60	31.58	74.05
2,500	0.700	3.038	9.891	26.65	62.25
3,000	0.637	2.719	8.739	23.38	54.47
3,500	0.592	2.494	7.926	21.04	48.87
4,000	0.558	2.324	7.303	19.29	44.77
5,000	0.512	2.088	6.444	16.90	38.87
6,000	0.481	1.933	5.820	15.32	34.89
7,000	0.457	1.823	5.491	14.17	31.96
8,000	0.439	1.748	5.211	13.29	29.76
9,000	0.424	1.689	5.003	12.61	28.00
10,000	0.414	1.648	4.834	12.07	26.61

have been determined by Reamer, Olds, Sage, and Lacey[2] for the vapor phase, and by Culberson, Horn, and McKetta[4] and Culberson and McKetta[3] for the liquid phase. Throughout this region of pressures and temperatures, only two phases were present at any time. The critical temperature of ethane is 90°F; therefore, an ethane-rich liquid phase was not present. Likewise, the conditions of temperature and pressure in the hydrate region[7] are not considered here.

With the vapor-liquid equilibrium data available, it was possible to calculate the equilibrium constants since by definition

$$K = y_i/x_i \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

In Equation (2), y_i is the mole fraction of component i in the vapor phase, and x_i is the mole fraction of the same component in the liquid phase.

Vaporization constants calculated by Equation (2) have been tabulated for ethane in Table I and plotted in Figs. 1 and 2. In Table II are tabulated the vaporization equilibrium constants for water in the ethane-water system. These constants for water are plotted in Fig. 3. In Fig. 3, it may be noted that at 100°F the equilibrium constant passes through a minimum and would probably continue to increase as the pressure increased to the convergence pressure.

METHANE-WATER SYSTEM

In the temperature range of 100° to 340°F and for pressures up to 10,000 psia, the vapor phase data were determined by Olds, Sage, and Lacey[2] and the liquid phase data by Culberson and McKetta.[3] As was the case in the ethane-water system, only the hydrocarbon-rich vapor phase and the water-rich liquid phase were present. The hydrate region is not covered, and the methane was above its critical temperature.

Equilibrium constants were calculated by Equation (2) and these values are tabulated in Table IV for methane and in Table V for water. Figs. 4 and 5 are plots of the equilibrium constants for methane. Equilibrium constants for water are shown in Figs. 6 and 7.

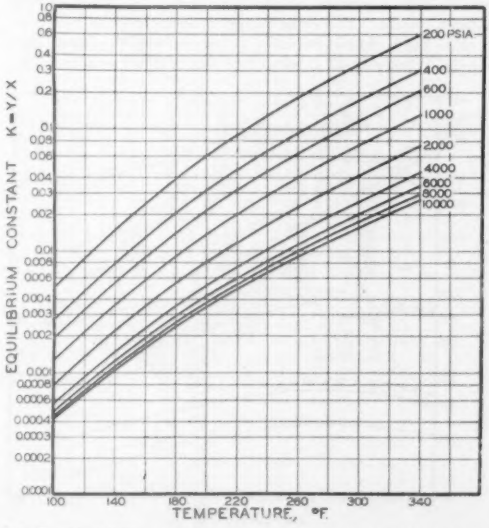
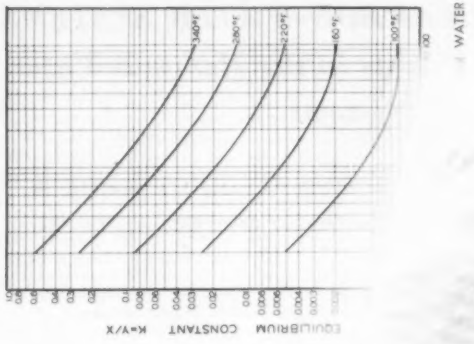
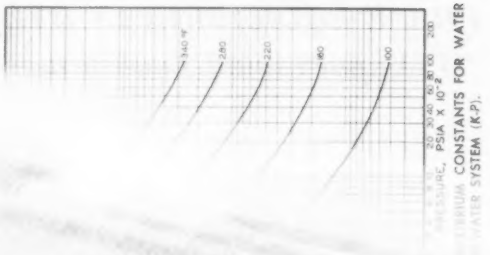


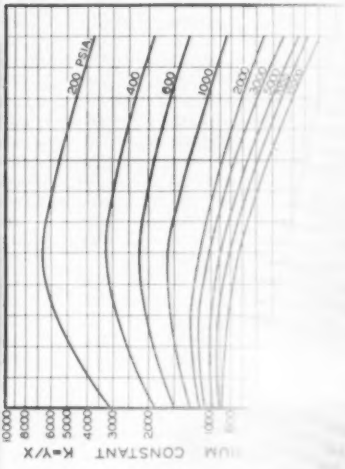
FIG. 7 — EQUILIBRIUM CONSTANTS FOR WATER IN METHANE-WATER SYSTEM (K-T).

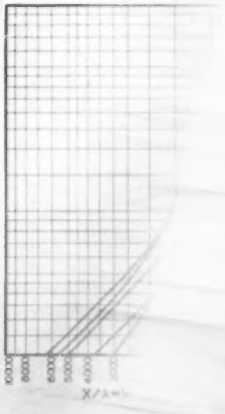
PHASE EQUILIBRIA IN HYDROCARBON-WATER SYSTEMS

IV—Vapor-Liquid Equilibrium Constants in the Methane-Water and Ethane-Water Systems









MEASURING THE WATER VAPOR CONTENT OF GASES DEHYDRATED BY TRIETHYLENE GLYCOL

IRWIN POLITZINER,* F. M. TOWNSEND, BLACK, SIVALLS AND BRYSON RESEARCH FELLOW, AND L. S. REID, MEMBER AIME, SCHOOL OF CHEMICAL ENGINEERING, UNIVERSITY OF OKLAHOMA, NORMAN, OKLA.

ABSTRACT

Recently published data indicate that the water vapor content of a gas, as determined by dew point measurement, is inaccurate when the gas has been dehydrated with diethylene glycol. Water vapor contents and dew point measurements of gases dehydrated with triethylene glycol have been obtained in order to determine the magnitude of

concentration of tri-
ted at atmospheric tem-
500 to 2,500 psia, and
urements is not impaired
vapor.

TION

ted by pipe line to northern
dehydrated to a low residual
ssure maximum transmission
ry under peak load conditions.
vapor often condenses in pipe
to restrict the flow[3] and, under
e conditions, gas hydrates may
transmission and distribution

ed to pipe line specifications by a
most widely used methods are (1)
por on a solid dessicant such as acti-
or silica gel,[1] (2) by absorption of
diethylene or triethylene glycol-water
ycol concentration,[11,12] and (3) by simul-
frigeration of very high pressure gas in
are purposely formed and then quickly
these three fundamental methods, the ad-
rption processes provide the bulk of the
owing to market at the present time. The
ration process, a relatively new development,
favor because of its simplicity but is sharply
application by available differentials between
gathering system pressures.

sale or purchase contracts contain a maximum
content specification, the water vapor content is
termined by measuring the dew point of the gas at
pressure. Knowing the dew point temperature and the
pressure, the water vapor content of the gas is deter-
from a graphical correlation of saturation, or dew point,
ture vs the water vapor content of the gas which is
narily expressed as pounds of water vapor per million
feet of gas measured at 14.7 psia and 60°F. Dew points

References given at end of paper.

Manuscript received in the office of the Petroleum Branch January 25, 1951. Paper presented at the Annual Meeting of the AIME in St. Louis, Mo., February 17-22, 1951.

*This paper is a condensation of a thesis submitted by Irwin Politziner in partial fulfillment of the requirements for the MChE degree conferred by the University of Oklahoma in June, 1951.

are usually measured with the U. S. Bureau of Mines Dew Point Tester, shown in Fig. 1, which is well suited for use at temperatures lower than 120°F and at pressures ranging from atmospheric to 3,000 psi. A number of correlations of dew point temperatures *vs* water vapor content are available,[3,8,15] the most recent of which is that by McCarthy *et al.*[4]

Where natural gas is dehydrated by absorbing contact with concentrated diethylene glycol-water solutions, considerable difficulty is experienced in observing water dew points due to condensation of liquid hydrocarbon and glycol films on the mirrored surface of the dew point tester. Riesenfeld and Frazier[12] report that the dew point method for determining the water vapor content of a diethylene glycol-treated natural gas is in error due to the glycol content of the condensate formed on the tester mirror, and that the water vapor content of the gas tested is actually lower than that indicated by the standard dew point-water vapor content correlation.

Extensive experience in testing gases dehydrated by concentrated triethylene glycol-water solutions has not revealed difficulties of the nature cited above for diethylene glycol. Water dew points are clear and sharp and condensation of

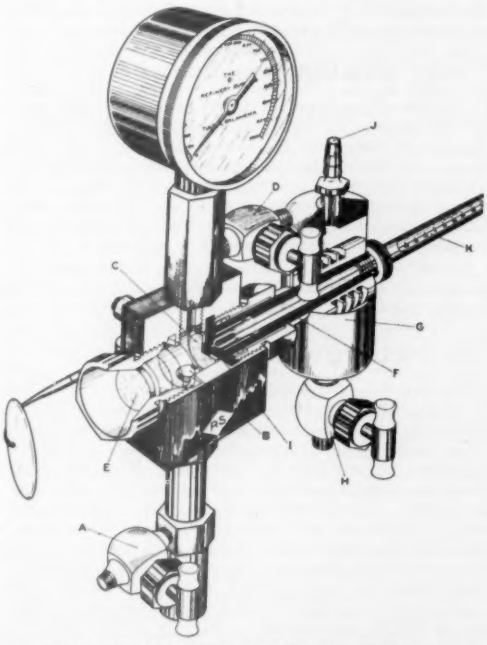


FIG. 1 — DEW POINT TESTER, U. S. BUREAU OF MINES TYPE.

DETERMINATIONS OF VAPOR-PHASE COMPOSITIONS

The apparatus which was used to obtain the liquid phase data had never been used to determine the composition of a vapor phase. For that reason it was decided to make vapor phase determinations in the ethane-water and methane-water systems to study the applicability of the apparatus to such work. Only qualitative results were sought, and an elaborate analytical train was not set up. The train used consisted of drying tubes containing magnesium perchlorate, a saturator where the dehydrated hydrocarbon was resaturated with water, and a receiving flask where the resaturated hydrocarbon was collected over water which had in turn been previously saturated with the hydrocarbon. The amount of water in the sample was taken to be the gain in weight of the drying tubes. The amount of hydrocarbon was calculated from PVT conditions in the receiving flask where the hydrocarbon pressure was taken to be the total pressure less the vapor pressure of water at the temperature within the flask.

The results of such determinations are given in Table III for the ethane-water system and in Table VI for the methane-water system. In the ethane-water system, the average deviation of the experimental values from the smoothed curve is probably slightly greater than the average deviation of the data of Reamer, Olds, Sage, and Lacey.[12] The average deviation for the methane-water system shown in Table VI compares with that of Olds, Sage, and Lacey.[11]

DISCUSSION

The equilibrium constants for methane and for ethane are compared with those for a natural gas in a natural gas-water system[6] in Fig. 8. It is shown that the constant for the ethane is greater than those of the methane and natural gas. The natural gas was 88.51 per cent methane; therefore, it is not surprising that its equilibrium constants were approximately the same as those of pure methane. The water solvent evidences two major effects which are not indicated in the equilibrium constants normally accepted in hydrocarbon-solvent systems.[3] The equilibrium constants for the hydrocarbons in the hydrocarbon-water systems are much greater than for the hydrocarbons in water-free hydrocarbon systems. Also,

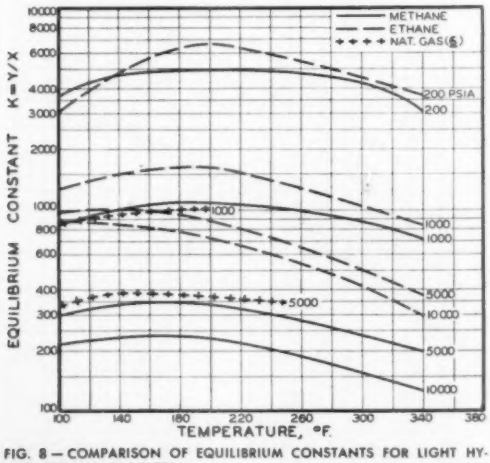


FIG. 8 — COMPARISON OF EQUILIBRIUM CONSTANTS FOR LIGHT HYDROCARBONS IN WATER.

Table VI — Experimental Determinations of Vapor Phase Composition in the Methane-Water System at 100°F

Pressure psia	Mole Fraction H_2O x 10^3 Experimental	Literature Smoothed[11]	Experimental % Deviation
758	1.770	1.580	+ 12.0
1,600	0.762	0.900	− 15.3
2,375	0.745	0.730	+ 2.06
3,615	0.483	0.580	− 16.7
5,185	0.502	0.515	− 2.52
		Average Deviation	9.72%

in the water-solvent systems, the equilibrium constants for the hydrocarbons pass through a maximum not common to the hydrocarbon-solvent systems.

No graphical comparison was made of the equilibrium constants for water in the systems. In the methane-water and ethane-water systems, the constants for water are almost identical under all the conditions studied except for conditions of high pressure and low temperature. The greatest difference occurred at 100°F and 10,000 psi where the constants differed by about 50 per cent (based upon the methane).

In systems such as these where the composition of the liquid phase is of the order of 99+ mole per cent water, the equilibrium constants for the hydrocarbon will be controlled by the liquid phase. When the very small mole per cent of hydrocarbon is used in the denominator of Equation (2), it affects the value of K for the hydrocarbon tremendously. In the same manner, the composition of the vapor phase controls the value of the equilibrium constant for water since the denominator of Equation (2) is always approximately unity.

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MEASURING THE WATER VAPOR CONTENT OF GASES DEHYDRATED BY TRIETHYLENE GLYCOL

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ABSTRACT

Recently published data indicate that the water vapor content of a gas, as determined by dew point measurement, is inaccurate when the gas has been dehydrated with diethylene glycol. Water vapor contents and dew point measurements of gases dehydrated with triethylene glycol have been obtained in this investigation in order to determine the magnitude of a similar error, if one exists.

Experimental data show a very low concentration of triethylene glycol vapor in gases dehydrated at atmospheric temperatures and pressures ranging from 500 to 2,500 psia, and that the accuracy of dew point measurements is not impaired by the presence of triethylene glycol vapor.

INTRODUCTION

Nearly all natural gas transported by pipe line to northern and eastern markets must be dehydrated to a low residual moisture content in order to assure maximum transmission efficiency and continuous delivery under peak load conditions. Without dehydration, water vapor often condenses in pipe lines in quantities sufficient to restrict the flow[3] and, under low atmospheric temperature conditions, gas hydrates may form and plug gathering, transmission and distribution facilities.

Gas may be dehydrated to pipe line specifications by a number of methods. The most widely used methods are (1) adsorption of water vapor on a solid dessicant such as activated bauxite, alumina or silica gel,[1] (2) by absorption of water vapor by either diethylene or triethylene glycol-water solutions of high glycol concentration,[13,12] and (3) by simultaneous expansion-refrigeration of very high pressure gas in which gas hydrates are purposely formed and then quickly decomposed.[10,11] Of these three fundamental methods, the adsorption and absorption processes provide the bulk of the dehydrated gas moving to market at the present time. The expansion-refrigeration process, a relatively new development, is gaining in favor because of its simplicity but is sharply limited in its application by available differentials between source and gathering system pressures.

Where gas sale or purchase contracts contain a maximum water vapor content specification, the water vapor content is usually determined by measuring the dew point of the gas at system pressure. Knowing the dew point temperature and the system pressure, the water vapor content of the gas is determined from a graphical correlation of saturation, or dew point, temperature *vs* the water vapor content of the gas which is customarily expressed as pounds of water vapor per million cubic feet of gas measured at 14.7 psia and 60°F. Dew points are usually measured with the U. S. Bureau of Mines Dew Point Tester, shown in Fig. 1, which is well suited for use at temperatures lower than 120°F and at pressures ranging from atmospheric to 3,000 psi. A number of correlations of dew point temperatures *vs* water vapor content are available,[2,5,15] the most recent of which is that by McCarthy *et al.*[4]

Where natural gas is dehydrated by absorbing contact with concentrated diethylene glycol-water solutions, considerable difficulty is experienced in observing water dew points due to condensation of liquid hydrocarbon and glycol films on the mirrored surface of the dew point tester. Riesenfeld and Frazier[12] report that the dew point method for determining the water vapor content of a diethylene glycol-treated natural gas is in error due to the glycol content of the condensate formed on the tester mirror, and that the water vapor content of the gas tested is actually lower than that indicated by the standard dew point-water vapor content correlation.

Extensive experience in testing gases dehydrated by concentrated triethylene glycol-water solutions has not revealed difficulties of the nature cited above for diethylene glycol. Water dew points are clear and sharp and condensation of

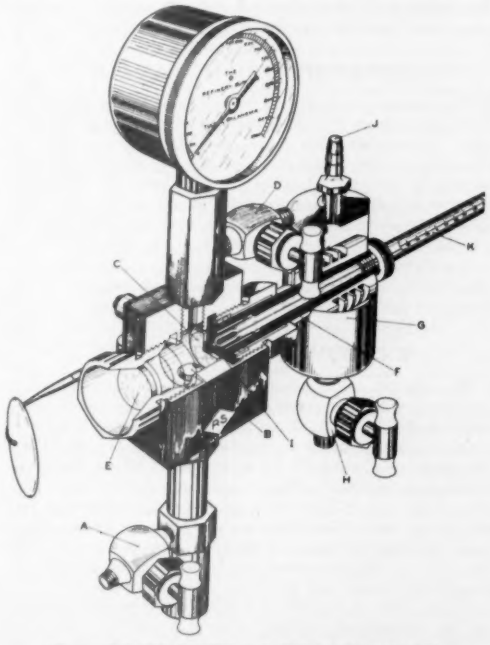

FIG. 1 — DEW POINT TESTER, U. S. BUREAU OF MINES TYPE.

[1]References given at end of paper.

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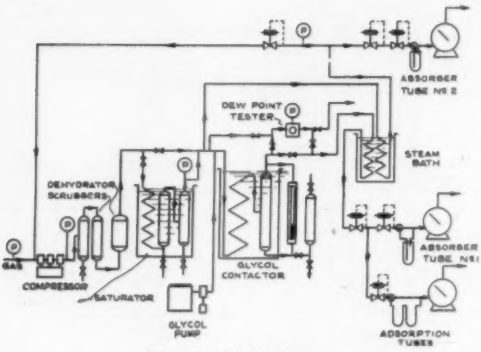

FIG. 2 — FLOW DIAGRAM.

glycol has not been observed except in those instances when the absorber has been substantially overloaded. Triethylene glycol has a vapor pressure substantially lower than that of diethylene glycol[4] and it is known that the vaporization losses of triethylene glycol[4] are considerably smaller than losses sustained when using diethylene glycol.[12] Preliminary investigations conducted by Porter *et al.*[5] failed to reveal any unusual discrepancy between water vapor contents determined by the dew point method and those determined by gravimetric analysis.

However, it has been assumed by many that the error reported in the water vapor content measurement of diethylene glycol-treated gases is also inherent in similar measurements where triethylene glycol is employed. The purpose of this investigation was to determine whether or not such an error exists and, if so, the magnitude of this error.

EXPERIMENTAL MATERIALS

The natural gas employed in this investigation was taken from the mains of the Oklahoma Natural Gas Co. at Norman, Okla. A representative analysis of this gas is shown in Table I. In view of the fact that this gas contains approximately 12 per cent air, several experimental determinations were made using oil-pumped nitrogen gas as the gas phase. This compressed nitrogen gas was obtained from the Air Reduction Magnolia Co. at Oklahoma City, Okla.

The triethylene glycol used was an air-treatment grade supplied by the Carbide and Carbon Chemicals Division, Union Carbide and Carbon Corporation.

EXPERIMENTAL EQUIPMENT

The dynamic equilibrium absorption apparatus described by Porter *et al.*[5] was employed in this investigation with only slight modifications, as shown in Fig. 2. The general plan of attack employed direct observation of the dew point of the dehydrated gas, using the U. S. Bureau of Mines Dew Point Tester and, simultaneously, determining the water vapor content of the gas by gravimetric analysis. The apparatus was modified to pass all glycol-treated gas through the dew point tester and, after heating in a hot water bath, the pressure was reduced to 60 psig by means of a pressure reducing regulator. Downstream from this regulator, the gas stream was split in two streams. One passed through a second regulator, where the gas pressure was reduced to near atmospheric, thence to two Pyrex adsorption tubes, filled with anhydrous magnesium perchlorate, thence to a wet test meter for measurement. The second stream was also passed through a pressure reducing regulator to expand the gas to near atmospheric pressure and passed into the bottom of Absorber Tube No. 1, consisting of a standard 10-in. test tube filled with glass Raschig rings and closed with a neoprene stopper. Glycol vapors were absorbed in distilled water in this device. Effluent gas passed to a second wet test meter for measurement.

A third sample stream of gas was taken from the apparatus upstream from the glycol contacting section, heated and expanded to near atmospheric pressure and passed in absorbing contact with fresh distilled water in a second absorption tube, designated as Absorber Tube No. 2 in Fig. 2. This glycol-free gas was used to determine the solubility of the natural gas in water, and employed in correcting the total glycol vapor and paraffin hydrocarbons absorbed in Absorber Tube No. 1. Effluent gas from this tube was passed to a wet test meter for measurement. Gas from all meters was vented to atmosphere.

EXPERIMENTAL TECHNIQUES

The experimental techniques employed in this investigation were essentially the same as those reported by Porter *et al.*[5] except for certain modifications outlined below.

All gas delivered to the apparatus by the compressor was dehydrated by adsorbing the moisture on a freshly reactivated charge of dessicant, and then re-saturated at the desired system temperature and pressure once those conditions had been established. It was found that this procedure would avoid condensation of water in the experimental apparatus.

Only that portion of the gas stream discharged by the compressor which was necessary for dew point and gravimetric analysis was passed through the glycol contactor. Most of the compressed gas was heated and then expanded to compressor suction pressure so that only the gas comprising the three sample streams was vented. All glycol-treated gas was passed through the dew point tester at all times to assure continuous flow at a steady rate and to eliminate any possibility of trapping gas with a variable glycol-water vapor content.

Triethylene glycol solution rates were established at 35 gal per standard Mcf of gas entering the absorber and this ratio was held constant during all experimental runs, regardless of pressure. Glycol solution concentrations were determined by the relative viscosity method described by Porter and Reid.[9]

The total quantity of gas passed through the adsorption train varied but the minimum quantity approximated 12 stand-

Table I — Analysis of Natural Gas

Component	Volume or Mol %
Carbon Dioxide	0.50
Oxygen	2.60
Nitrogen	14.05
Methane	67.29
Ethane	9.50
Propane	4.27
Butanes	1.36
Pentanes	0.31
Hexane and Heavier	0.12
	100.00
Specific Gravity	0.7470

ard cu ft. Magnesium perchlorate was chosen as the adsorbent because it extracts virtually all vapors from a gas stream. A final concentration of 0.002 mg of water vapor per liter of gas is reported for this desiccant.[2] A 40 mg increase in weight of the drying tubes was desired in order to minimize weighing errors.

The adsorption tubes were weighed on an analytical balance before and after each run and care was taken to replace the tubes in the train in the same order after each weighing. When the weight gained by the second tube exceeded five per cent of that gained by the first, the desiccant in the first tube was replaced. Prior to use, dehydrated gas was always passed through a freshly charged tube to displace the air and to saturate the desiccant with any adsorbable components of the gas.

Eight standard cu ft of gas was passed through Absorption Tube No. 1, and an identical quantity was passed through Absorption Tube No. 2. Residue gas streams from the adsorption train and the two absorption tubes were measured to 1/1000 cu ft and then corrected to standard conditions of 29.92 in. of mercury and 60°F.

The quantity of triethylene glycol vapor in the gas stream was determined by reacting the liquid contents of Absorption Tube No. 1 with potassium dichromate and concentrated sulfuric acid and, after the oxidation-reduction reaction was complete, titrating the excess potassium dichromate with ferrous-ammonium sulfate. A correction for hydrocarbons dissolved in water was determined by subjecting the liquid contents of Absorption Tube No. 2 to the same procedure. Complete details of this analytical procedure are reported by Politziner.[7]

Results of these analyses were computed in terms of grams of triethylene glycol vapor per standard cubic feet of gas and this quantity was subtracted from the grams of water and glycol vapor adsorbed per standard cubic foot of gas. The remainder was the grams of water vapor per standard cubic foot which was then converted to pounds of water vapor per standard million cubic feet of gas. This result was used to predict the dew point of the gas from the correlation of McCarthy *et al.*[4]

Although the water vapor content was obtained by difference, the results are quite accurate because the quantity of triethylene glycol vapor present in the gas was found to range from one to three per cent by weight of the total glycol and water vapor content. See Table II.

Since McCarthy's correlation pertains to essentially nitrogen-free gas, several experimental runs were made employing oil-pumped nitrogen as the gas phase, replacing the air-diluted natural gas used in the major portion of this research. It was felt that this series of special runs might throw some light on the effect of nitrogen on the water vapor content of nitrogen-bearing natural gas mixtures.

Table II — Triethylene Glycol in the Gas Stream — Weight Per Cent of Total Glycol and Water Vapor Content

System Temperature: 80°F

Run No.	TEG Concentration Weight Per Cent	System Pressure psia	Lbs. TEG Vapor Per 100 lbs. TEG and Water Vapor in Effluent Gas
15	99.5	500	1.28
29	95	1,000	1.29
16	99.5	1,000	1.33
27	95	1,500	2.13
17	99.5	1,500	4.84
28	95	2,000	2.12
9	99.5	2,000	2.32
26	95	2,500	3.37
19	99.5	2,500	3.44

Table III — Comparison of Observed and Calculated* Water Dew Points of Natural Gas Dehydrated By Triethylene Glycol

Run No.	TEG Concentration % by Wt.	System Temp. °F	System Press. psia	Water Content per std. MMcf	Calculated dew point °F	Observed dew point °F	Difference between calculated and observed dew points °F
30	95	80	500	17.10	43	43.5	+ 0.5
29	95	80	1,000	10.30	43	39	− 4
20	99.5	70	1,000	2.92	11	12.5	+ 1.5
16	99.5	80	1,000	4.78	22.5	19	− 3.5
37	99.5	90	1,000	6.37	30	30	0
27	95	80	1,500	7.19	42	40.5	− 1.5
28	95	80	2,000	7.85	49	47	− 2
9	99.5	80	2,000	3.41	26	25	− 1
23	99.5	90	2,000	2.40	17.5	20	+ 2.5
35	95	90	2,000	9.71	55	56.7	+ 1.7
36	99.5	90	2,000	6.02	41	43.3	+ 2.3
26	95	80	2,500	7.22	50	49.5	− 0.5

*Based on correlation by McCarthy, Boyd and Reid[4]

DISCUSSION OF RESULTS

Experimental determinations of water vapor content of glycol-dehydrated natural gas were made at pressures ranging from 500 to 2,500 psia and at system temperatures of 80 and 90°F, employing solutions of 95 and 99.5 per cent by weight triethylene glycol, the remainder being water. Six additional determinations were made in which oil-pumped nitrogen gas replaced the natural gas. All nitrogen runs were conducted at 80°F with pressures ranging from 500 to 2,000 psia, employing glycol solutions of the concentrations noted above.

The results obtained from this investigation are shown in Table III, where observed dew points are compared to dew points calculated from the gravimetric analyses by means of McCarthy's correlation. Inspection of these data show that, in general, the discrepancy between observed and calculated dew points is approximately two degrees F; also that these discrepancies are quite evenly distributed, plus and minus, indicating a small experimental error in manipulating the dew point tester at the low flow rate imposed by gravimetric sampling limitations. It is also significant to note that lower dew points were obtained when the gas was dehydrated by the 99.5 per cent glycol solution. The relatively low residual water vapor content of gas dehydrated in this manner tended to magnify the discrepancy between observed and calculated dew points. With but one exception, the greatest discrepancies are associated with determinations in which this highly concentrated solution was employed. A similar distribution was noted in the nitrogen runs, as shown in Table IV.

Three separate and distinct dew points were observed during this investigation. Fortunately, they are not similar in appearance and distinctions are readily drawn. The first of these is a hydrocarbon dew point which appears as a bright, highly mobile liquid film cascading across the mirror. This cannot be confused with a water dew point because of its distinctive appearance and because it appears almost immediately after cooling is begun. Where hydrocarbon condensation is severe and liquid accumulates in the dew point tester to the extent that it is cycled against the mirror by the gas jet, the entire body of the tester should be inverted. This will permit the liquid to drain off as fast as it is formed.

The second dew point appears to be a thin film of glycol which accumulates gradually on a clean mirror and forms a haze. This film does not disappear when the tester tempera-

Table IV — Comparison of Observed and Calculated* Water Dew Points of Nitrogen Dehydrated By Triethylene Glycol

Run No.	TEG Concentration % by Wt.	System Temp. °F	System Press. psia	Water Content lbs. per std. MMcf	Calculated dew point °F	Observed dew point °F	Difference between calculated and observed dew points °F
32	95	80	524	21.55	51	49.5	−1.5
40	99.5	80	524	6.17	17.5	21	+3.5
41	99.5	80	1,000	3.35	14	18.7	+4.7
31	95	80	1,500	9.35	48	45.5	−2.5
42	99.5	80	1,500	2.62	15	19	+4
33	95	80	2,000	8.15	50	49.5	−0.5

*Based on correlation by McCarthy, Boyd and Reid[4]

ture is raised or when its pressure is released. It has not been observed during tests on commercial dehydration units using triethylene glycol, so the formation of this film is believed to be an inherent characteristic of the experimental apparatus.

As cooling is continued, a third dew point is observed. It appears as a dark spot in the center of the mirror and, if temperature and pressure conditions are conducive to hydrate formation, gas hydrate crystals will be observed forming in this spot immediately after it appears. The temperature at the instant the spot first appears is the water dew point.

True equilibrium distribution of water between the vapor and liquid phases was not obtained in the absorber during this investigation because of absorber velocity restrictions imposed by the gravimetric sampling rates. However, the degree of dehydration accomplished here was of the same order of magnitude as that of most commercial dehydration units. In view of this similarity in performance, Fig. 3 has been prepared as a smoothed plot of a portion of the data of Table II, showing the magnitude of triethylene glycol vapor losses as a function of absorber pressure when operated at 80°F. The glycol concentration of the solution is the parameter. It is significant to note that the triethylene glycol concentration in the effluent gas from the absorber is very low and that this concentration reaches a minimum value in the vicinity of 1,000 psia. The low loss incurred by use of 95 per cent triethylene glycol solution may be even further reduced by increasing the glycol concentration. Glycol vapor losses are well within the limits of sound operating practice when the absorber pressure is as high as 2,500 psia.

The data of Table II indicate that the triethylene glycol vapor concentration in dehydrated gas is unusually small, ranging from one to three per cent by weight of the total water vapor plus glycol vapor content of the gas. Since but a small fraction of this glycol vapor would be condensed when the water dew point was formed, its presence would have a negligible effect. These data lend strong support to the comparisons drawn in Tables III and IV.

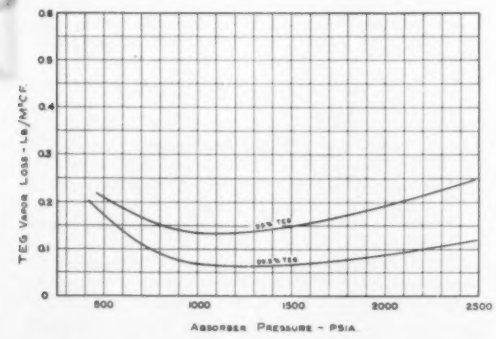

FIG. 3 — TRIETHYLENE GLYCOL VAPOR LOSSES AS A FUNCTION OF PRESSURE AND SOLUTION CONCENTRATION AT 80°F.

CONCLUSIONS

In conclusion, it is evident that:

1. The water vapor content of triethylene glycol-dehydrated gases may be determined accurately by dew point measurement.
2. The quantity of triethylene glycol vapor present in a stream of dehydrated gas is very small, ranging from one to three per cent of the total glycol-water vapor content of that gas.
3. Triethylene glycol vapor losses are, in general, less than 0.2 lb of glycol per standard MMcf of gas processed, over the ranges of temperature, pressure and solution concentration reported here.
4. Triethylene glycol vapor losses may be reduced to a substantial degree by maintaining the glycol concentration of the solution greater than 95 per cent by weight.
5. The water vapor content-saturation temperature correlation by McCarthy *et al.* is accurate for triethylene glycol-dehydrated gases whose specific gravities range as high as 0.75.
6. The variable nitrogen content of a natural gas mixture apparently has scant effect upon its water vapor content.

ACKNOWLEDGMENTS

The air-treatment grade triethylene glycol used in this investigation was furnished by the Carbide and Carbon Chemicals Division of Union Carbide and Carbon Corp.

The oil-pumped nitrogen and the nitrogen storage facilities were furnished by Black, Sivalls and Bryson, Inc.

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THE LATEROLOG: A NEW RESISTIVITY LOGGING METHOD WITH ELECTRODES USING AN AUTOMATIC FOCUSING SYSTEM

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ABSTRACT

A new electrical logging method called Laterolog is described which provides for better recording of formation resistivity. In this method a current, preferably of constant intensity, is forced into the formation perpendicularly to the wall of the hole as a sheet of predetermined thickness by means of a special electrode arrangement and of an automatic control system.

The essential advantages of the Laterolog over the regular resistivity logs are explained. With the Laterolog, the mud column has much less influence than with conventional methods. The Laterolog is, therefore, particularly useful in wells drilled with highly conductive mud. Moreover, when the electrode system is located opposite a bed of moderate or small thickness, the disturbing effect of the adjacent formations becomes practically eliminated, provided the bed is thicker than the sheet of current, which itself is usually a few inches to a few feet thick. The sequences of beds are, therefore, much more sharply differentiated, and, in many cases, it is possible to read directly from the logs values close to the true resistivities of the formations without further corrections.

Field examples are shown to illustrate the results of the method in various types of formations.

INTRODUCTION

As soon as it was introduced into the petroleum industry, electrical logging proved to be a powerful instrument for the delineation of the strata traversed by bore holes and for correlation of such strata.[1,2] Research and engineering efforts were mostly devoted at this early time to the design of the techniques which could provide the best data for these purposes.

Later, attention was directed toward the quantitative analysis of electrical logs, in order to obtain information on reservoir characteristics, and, in particular, on oil and water saturation.[3,4] Efforts have been made, accordingly, with a view to improving the already existing methods, or to finding new methods which could satisfy these new requirements.[5]

Quantitative analysis implies a determination as accurate as possible of the true resistivity of the formations. In fact, however, the "apparent resistivity" recorded in front of a given bed by a conventional electrical logging method is frequently quite different from the true resistivity of this bed. This is due to the combined influence of the mud column, of the adjacent formations both above and below the bed, and of the invaded zone, in which the original fluid has been more or less replaced by mud filtrate.

When the beds are thick enough, and, as is frequently the case in sand and shale formations, when their resistivity is not much greater than that of the mud, it is generally possible to obtain their true resistivity directly on the electric log, or at least to obtain an approximate value which can be corrected without undue difficulty by means of recently published charts known as "departure curves."[6]

When the beds are thin, and particularly when, in addition, their resistivity is substantially greater than that of the mud column, the apparent resistivities recorded on conventional logs are seriously affected, and it is generally very difficult, if at all possible, to estimate their true resistivity with a good enough accuracy. In the most severe cases, such as are encountered in holes drilled through hard formations with muds of high salinity, the conventional logs are so distorted and rounded that they do not even show clearly the boundaries of the different beds.

In order to overcome the effect of the mud column and of the adjacent formations, it is possible to make use of appropriate systems whereby the measurements involve a comparatively thin slice of space at the level of the measuring device.

A mention is due, in this respect, to a measuring system, called the "guarded electrode," invented by C. Schlumberger over 20 years ago. The system, schematically represented in

[1]References given at end of paper.

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Fig. 1, comprises one short central electrode M and two elongated short-circuited electrodes, G and G' symmetrically placed above and below M, and connected to M by a low resistance shunt S. A current is fed to the electrodes, and that part i of the current which flows through the central electrodes forms a sheet which is confined between two approximately horizontal surfaces. The current i is measured by means of a meter located at the surface and connected to both ends of the shunt. The potential ΔV of electrode M is also measured by means of another meter at the surface, and the ratio $\frac{\Delta V}{i}$ gives the value of the resistance offered to the current, which resistance is proportional to the resistivity of the formation situated within the current sheet. The guarded electrode makes possible a detailed investigation of thin beds; however, the presence of a long metallic body in the bore hole amounts to short-circuiting the spontaneous current, and may deteriorate the SP log, and furthermore measurements of resistivities with other electrical devices recording at the same level are made practically impossible. Moreover, because of the presence of the shunt, the potential of the guard electrodes is not rigorously equal to the potential of the central electrode, but is greater by an amount which depends on the resistance of the shunt and on the resistivity of the surrounding media. The shape of the beam of current emitted by electrode M is, therefore, affected to an extent which cannot easily be ascertained, and, consequently, the response of the system is not quite defined, particularly when the bore hole is filled with low resistivity mud.

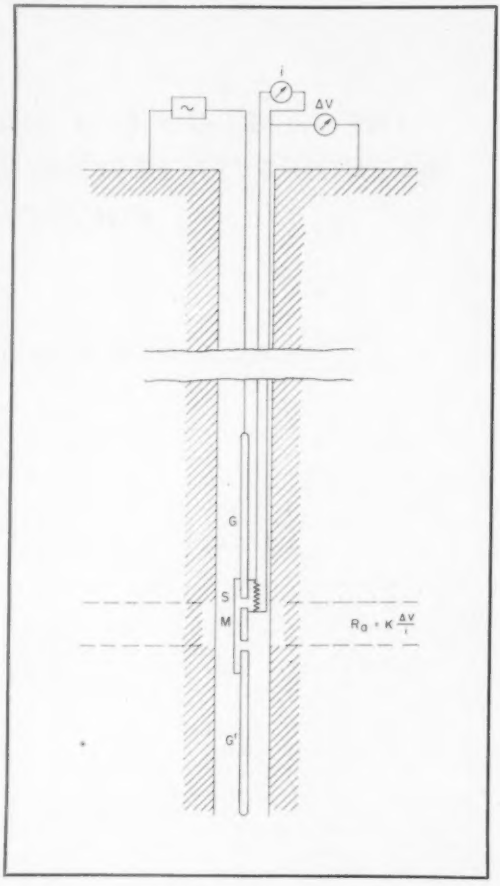

FIG. 1 — GUARDED ELECTRODE

Along the same line, mention is also made of the interesting work done by the Pennsylvania State College.[7,8]

Mention must be made also of the Induction Logging method, which was the subject of an earlier paper,[9] and in which a focusing effect is obtained by an appropriate combination of coils.

The Laterolog system, which is described in this paper, is a new electrical logging method which makes use of a sheet of current of constant intensity and of well calibrated thickness, focused by means of an automatic control. This system furthermore can be used with point electrodes, which, among other advantages, make possible the simultaneous recording of the SP curve, or other electric logs.

With the Laterolog device, the effect of the mud column can always be neglected, and the effect of the adjacent formations is practically eliminated in all beds whose thickness is greater than that of the focused sheet of current; *i.e.*, from a few inches to a few feet, depending on the electrode combination being used.

Were it not for the invaded zone, a Laterolog would show directly the true resistivity of all beds whose thickness is greater than the limit mentioned above. In practice, the resistivity, as recorded, is quite close to the true value when the diameter of the zone invaded by the mud filtrate does not exceed about two to three times the diameter of the hole, and provided that the resistivity of the invaded zone is not greater than the true resistivity of the bed under investigation. This condition is frequently satisfied for oil-bearing formations, especially when the salinity of the mud is not much lower than that of the connate water.

Because of the comparatively small thickness of the focused sheet of current, the Laterolog gives a very detailed curve, and puts clearly in evidence the sharp contrasts between successive beds, however conductive the mud may be.

The first applications of the Laterolog method have been in holes drilled with high salinity mud. In that case, logs showing sharp contrasts and great details are obtained, where conventional methods would have given quite distorted and rounded curves. Furthermore, and because of the low resistivity of the mud filtrate in that case, the resistivities as recorded on the log are close enough to the true values. Typical examples of Laterologs run under such conditions are shown in Figs. 12, 13 and 14.

More generally, the Laterolog is quite useful in all hard formations because it eliminates the effect of the mud column and of the adjacent formations, which are generally quite large in that case for the conventional methods. It will always give a detailed picture of the formations, and a sharp definition of the boundaries. Whenever the resistivity of the mud filtrate is too great for the effect of the invaded zone to be neglected, the true resistivity will not be read directly from the Laterolog, but corrections could be introduced if the depth of penetration of the mud filtrate, and the resistivity

of the invaded zone can be estimated or determined with the help of some other electrical log, which could be, for example, a Laterolog with a smaller depth of investigation.

Qualitatively, in sand and shale formations, the advantage of the Laterolog is not so pronounced since there the conventional logs give a satisfactory answer. The usefulness of the Laterolog in that case will, therefore, depend on its ability to contribute to the determination of the true resistivity of the sands. Unfortunately, the muds that are generally used, in the Gulf Coast and Louisiana, for example, have a salinity which is much lower than that of the connate water, so that many sands, even good oil producers, are less resistive than the invaded zone. Here again, the determination of true resistivity from the Laterolog alone will be generally possible only when the effect of the invaded zone can be estimated by other means.

It is reasonable to envisage that for most formations the best way to accomplish the determination of true resistivity, both in the case of thick and of thin beds, will consist in simultaneously recording a Laterolog and an Induction Log, when the complete development of this last method is achieved.

PRINCIPLE OF THE LATEROLOG

The Laterolog device (Fig. 2) comprises one electrode A_o, and three pairs of electrodes, M_1M_2, $M'_1M'_2$, A_1A_2, positioned symmetrically with respect to A_o, with the pairs being respectively short-circuited. A current of constant and calibrated intensity is fed through electrode A_o. Additional currents of same polarity as the current flowing through A_o are fed through the auxiliary power electrodes A_1 and A_2. The intensity of these currents is automatically and continuously adjusted in such a way that the difference of potential between M_1M_2 and $M'_1M'_2$ is maintained substantially equal to zero. The potential prevailing at any one of these latter four electrodes is recorded. The apparent resistivity measured with the device is proportional to the value of this potential and to a certain geometrical factor which depends on the distances between the various electrodes.

According to this system, the current emitted from A_o is prevented from flowing upward and downward past the meas-

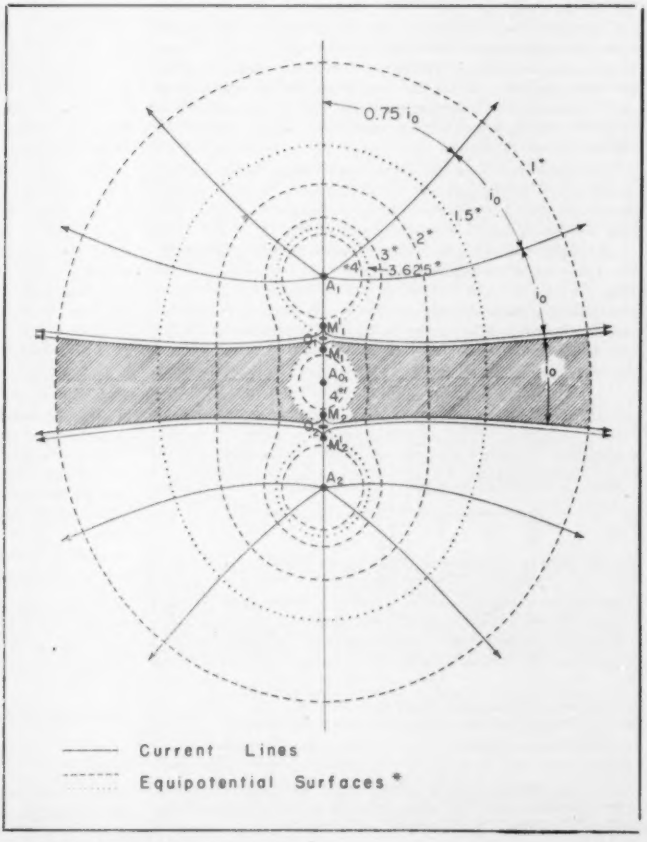

FIG. 2 — LATEROLOG: EQUIPOTENTIAL LINES AND LINES OF CURRENT FLOW IN HOMOGENEOUS MEDIUM (COMPUTED). *TO OBTAIN THE POTENTIALS IN MV MULTIPLY THE FIGURES BY $\frac{R i_o}{4\pi a}$ WITH a IN METERS, R IN OHM-METERS, AND i_o IN MILLIAMPERES.

uring electrodes $M_1M'_1$ and $M_2M'_2$, as if insulated plugs were placed in the hole at the level of these electrodes. Accordingly, the mud column, which handicaps seriously the conventional logs when the formations are much more resistive than the mud, has very little influence on the measurements made with the Laterolog. Moreover, the electrical conditions created by the controlling system are such that the current emitted by A_o behaves as if the insulated plugs were extended horizontally far away from the bore hole. The current is therefore obliged to flow within an approximately horizontal slice of space, whose thickness is about equal to the distance separating the middle points O_1 and O_2 of $M_1M'_1$ and $M_2M'_2$.

Fig. 2 shows the distribution of the current lines and of the equipotential surfaces for a Laterolog device placed in a homogeneous medium. The sheet of current issued from A_o, represented by a shaded area, is bounded by two surfaces, which up to a considerable radial distance from the drill hole are close to the two horizontal planes passing through O_1 and O_2. The potential of any of the electrodes M_1, M'_1, M_2, M'_2 represents the drop of potential produced by ohmic effect in the sheet of current, from its origin in the bore hole to a large distance from the hole; and is therefore proportional to the resistivity of the medium. The volume of ground where the resistivity is measured is essentially a horizontal slice, having the same thickness and the same position as the sheet of current.

To explain the operation of the system in the case of thin beds, it is convenient to consider that it is placed in front of a homogeneous bed — referred to as "the bed" — having the same thickness as the current sheet, and bounded above and below by thick homogeneous formations — respectively referred to as upper and lower formations, and to neglect the effect of the mud column.

If the resistivities of the upper and lower formations are equal to that of the bed, the situation is substantially that of an infinite homogeneous medium, and the distribution of current and potentials is as represented in Fig. 2. If it is now assumed that the upper and lower formations are, for example, ten times more conductive than the bed, the auxiliary currents flowing through A_1 and A_2 are automatically increased to about ten times what their value would be in a homogeneous medium — otherwise the potential differences at $M_1M'_1$ and $M_2M'_2$ would not be nil — so that the distribution of potential above and below the bed is automatically brought back to what it would have been in the homogeneous medium. There is, therefore, no tendency for the current of the sheet to be attracted by the upper and lower conductive beds. The sheet of current keeps nearly its normal shape, and produces in the bed a drop of potential which is practically the same as if the bed had been considerably thicker. The apparent resistivity observed opposite the center of the bed is therefore very little different from the true resistivity of the bed.

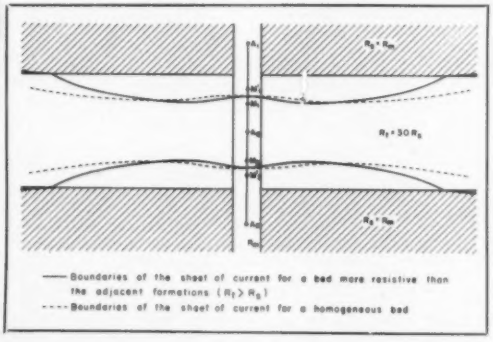
$R_s = R_m$
$R_t = 30 R_s$
$R_s = R_m$
Boundaries of the sheet of current for a bed more resistive than the adjacent formations ($R_t > R_s$)
Boundaries of the sheet of current for a homogeneous bed

FIG. 3 — LATEROLOG — SHAPE OF THE SHEET OF CURRENT (LABORATORY DETERMINATION). R_t: RESISTIVITY OF BED. R_s: RESISTIVITY OF ADJACENT FORMATIONS. R_m: RESISTIVITY OF MUD.

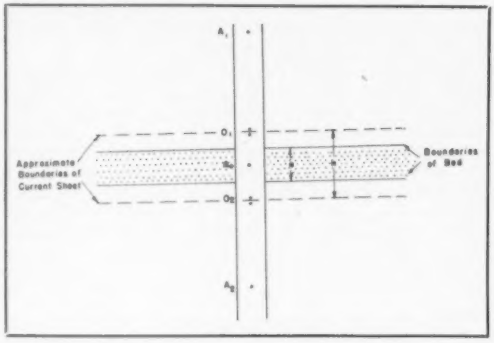

FIG. 4 — LATEROLOG DEVICE OPPOSITE A BED WHOSE THICKNESS IS LESS THAN THE THICKNESS OF THE SHEET OF CURRENT.

When the upper and lower formations are more resistive than the bed, the auxiliary currents are automatically decreased, and an equivalent result is obtained.

The result is practically the same when the sheet of current penetrates a homogeneous bed that is thicker than the current sheet, and the apparent resistivity is again substantially equal to the true resistivity of the bed. As an illustration, Fig. 3 shows the shape of the sheet of current, determined by laboratory experiments, for the case of a bed more resistive than the adjacent formations, and slightly thicker than the sheet of current. For comparison, the shape of the sheet of current, for the same pattern of electrodes, but in the case of a homogeneous medium, is shown in the figure.

In the converse case of a bed whose thickness is smaller than that of the sheet of current, the constant current from A_o divides itself, according to conductivities and respective thicknesses of the bed and that part of the surrounding formations which is within the lower and upper limits of the sheet of current. The apparent resistivity, as recorded, is in that case an average between the resistivity of the bed and that of the surrounding formations, and depends, of course, on the thickness of the bed. Furthermore, the presence of the more conductive formation within the sheet has a predominant effect on the apparent resistivity.*

*It is supposed (Fig. 4) that e is the thickness of the bed and h the thickness of the sheet of current, R_t the resistivity of the bed and R_s the resistivity of the adjacent formations. Since the current lines from A_o are all practically horizontal starting at a certain distance from the bore hole, the average, or apparent resistivity R_a measured with the device may be computed approximately through the equation:

$$\frac{h}{R_a} = \frac{e}{R_t} + \frac{h-e}{R_s}$$

If, for example, R_t is taken equal to 10, R_s to 1, h to 2 and e to 1, then:

$$\frac{2}{R_a} = \frac{1}{10} + \frac{1}{1} = 1.1$$

hence

$$R_a = \frac{2}{1.1} = 1.8 \text{ so that } R_a = 0.18\ R_t$$

If, conversely, $R_t = 1$ and $R_s = 10$ with the same values for h and e, R_a is again found equal to 1.8, so that $R_a = 1.8\ R_t$.

In order to explain why the Laterolog is better adapted for the investigation of thin beds, it will be compared to a normal device, in the following schematical example of a thin bed of high resistivity R_t, non-invaded and bounded by thick formations of low resistivity R_s, with the thickness of the bed being slightly greater than that of the sheet of current (Fig. 5).

Fig. 5 is divided into two parts by a vertical dash-dot line which coincides with the axis of the bore hole. A power electrode A is shown on the axis mid-way between the boundaries of the bed. The distribution of the current emitted from electrode A, without any focusing system — case of normal device — is represented qualitatively on the left-hand part of the figure. The distribution corresponding to the use of a focusing system — case of the Laterolog — is shown in the right-hand part.

The apparent resistivity is proportional to the potential prevailing at an electrode M, close to the power electrode A, and consequently to the resistance between the equipotential surface passing through M, and infinity. In the case of the device without focusing system (left-hand side of Fig. 5), the current lines diverge from A in all directions and are definitely attracted upward and downward by the adjacent formations, more conductive than the bed, so that the resistance offered by the bed to the current is, to a great extent, by-passed. The apparent resistivity read opposite the bed is therefore much lower than the true resistivity of the bed. With the Laterolog, on the contrary (right-hand side of Fig. 5), all the current lines flow within the boundaries of the bed, at least for a large distance from the bore hole, so that the resistance between the equipotential passing through M, and infinity, and accordingly the potential at M, is directly controlled by the resistivity of the bed. The apparent resistivity then is very close to the true resistivity of the bed.

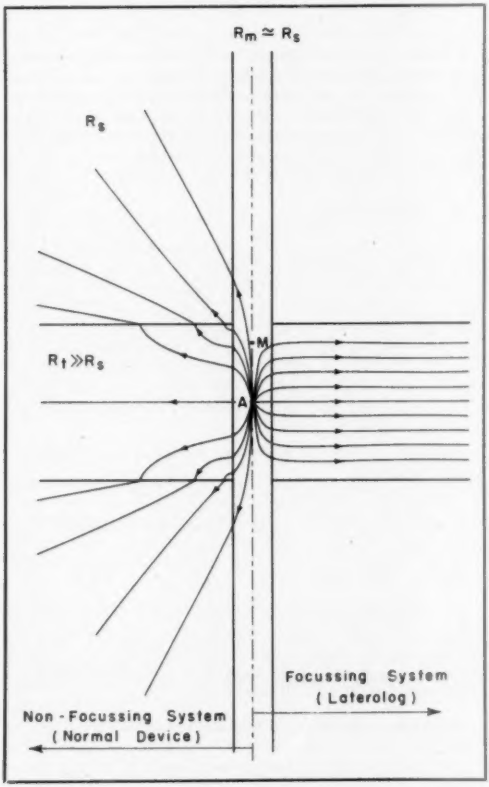

FIG. 5 — COMPARISON OF THE DISTRIBUTIONS OF THE CURRENT LINES IN THE CASE OF A NORMAL DEVICE, AND OF THE LATEROLOG, THIN BED MORE RESISTIVE THAN ADJACENT FORMATIONS. (SCHEMATIC DRAWING.) R_t: RESISTIVITY OF BED. R_s: RESISTIVITY OF ADJACENT FORMATIONS. R_m: RESISTIVITY OF MUD.

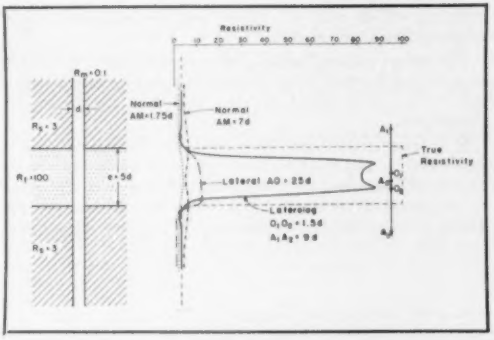

FIG. 6 — RESPONSE OF LATEROLOG AND CONVENTIONAL DEVICES OPPOSITE A THIN RESISTIVE BED, NON-INVADED, WITH LOW RESISTIVITY MUD (LABORATORY DETERMINATION). d: DIAMETER OF HOLE. e: THICKNESS OF BED $= 5d$. R_t: RESISTIVITY OF BED $= 100$. R_s: RESISTIVITY OF ADJACENT FORMATION$=3$. R_m: RESISTIVITY OF MUD$=0.1$.

This simple example was given to illustrate schematically the comparative behavior of the normal and the Laterolog devices. Similar comparisons could be made for other cases, but a complete review would be too long to be contained within the scope of this paper.

These general indications on the characteristics of the Laterolog will be made more precise by the results of a laboratory experiment given as example, and of theoretical studies, relative to the determination of true resistivity.

LABORATORY EXAMPLE OF LOGGING IN THIN BED

Fig. 6 shows a typical example of a curve recorded in the laboratory with a Laterolog device opposite a thin bed, more resistive than the adjacent formations, and traversed by a bore hole filled with mud of low resistivity.

In Fig. 6 the thickness of the bed e is equal to five times the hole diameter d. The spacing of the Laterolog device is $O_1O_2 = 1.5d$, with A_1A_2 being equal to six times O_1O_2. For a usual value of hole diameter, say about 9 in., these values correspond respectively to a bed thickness slightly less than 4 ft, and to a thickness of the current sheet slightly greater than one ft. The resistivity of the bed R_t is equal to 100, the

resistivity of the mud R_m to 0.1, and the resistivity of the adjacent formations R_a to 3.

The curves recorded with a short normal $AM = 1.75d$ (16 in.), a long normal $AM = 7d$ (64 in.) and a lateral device $AO = 25d$ (18 ft 8 in.) are also shown on the figure, for comparison.*

It is seen in the figure that the Laterolog device gives a much sharper and more accurate indication of the boundaries of the bed than the conventional deviecs. Moreover, the value of the apparent resistivity read with the Laterolog on the center plane of the bed is equal to 80, *i.e.*, only 20 per cent less than the true resistivity, whereas the normal devices and the lateral device show respectively 4, 5 and 12 instead of 100.

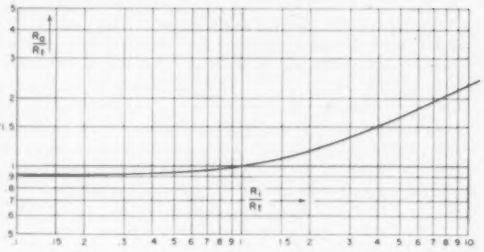

FIG. 8 — RESPONSE OF THE LATEROLOG DEVICE A, BED OF INFINITE THICKNESS, DIAMETER OF INVADED ZONE $D_i = 2d$ (APPROXIMATE COMPUTATION). R_t: RESISTIVITY OF BED. R_a: RESISTIVITY OF ADJACENT FORMATIONS. R_i: RESISTIVITY OF INVADED ZONE. R_a: APPARENT RESISTIVITY.

DETERMINATION OF THE TRUE RESISTIVITIES

The purpose of the Laterolog is not only to give a detailed qualitative delineation of the beds but also to provide directly on the log values close to the true resistivity of the beds, whatever their thickness, provided, of course, this thickness is not exceedingly small.

*The lateral curve, traced on the figure, has not been determined in the laboratory because of the insufficient size of the experimental tank. This curve is derived from the computation made, supposing the bore hole effect negligible. The maximum apparent resistivity thus computed is likely to be somewhat higher than the value which would be observed if the bore hole effect were taken into account.

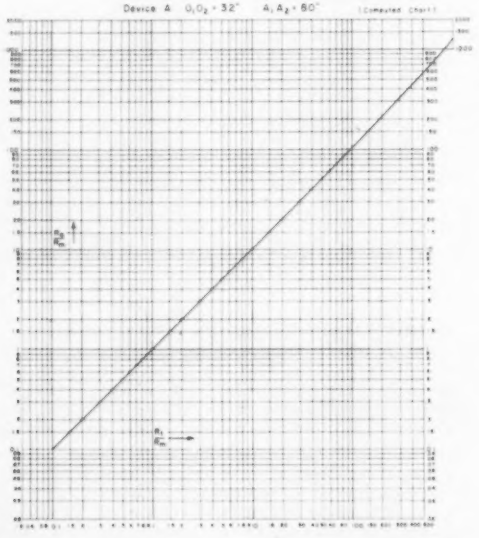

FIG. 7 — RESPONSE OF LATEROLOG DEVICE, HOMOGENEOUS BED OF INFINITE THICKNESS, NO INVASION.

In order to realize what is the capability of the Laterolog in this respect, it is convenient to examine first its response with reference to true resistivity determination in the simple case of very thick beds — then how its response is affected by the presence of adjacent formations in the case of thin beds. These two cases will be considered hereafter.

Case of Thick Beds

The value of the apparent resistivity measured with a Laterolog device can be computed exactly in terms of the various factors involved: true resistivity of the bed, mud column, and invaded zone, if any. It is thus possible to determine what distances should be selected between the electrodes to give the best possible response. The criterion, in this respect, is to obtain values of apparent resistivities R_a as close as possible to the values of true resistivity R_t, in a non-invaded formation for any ratio of the resistivity R_t of the bed to the resistivity R_m of the mud.

The chart of Fig. 7 is related to the following combination, called "device A":

$$O_1O_2 = 32 \text{ in. and } A_1A_2 = 80 \text{ in.}$$

In this chart, the values of $\frac{R_a}{R_m}$ recorded with device A are plotted in terms of the values of $\frac{R_t}{R_m}$.

The computations have been made for two widely different values of the hole diameter (namely 8 in. and 13 in.) — but the results have been found practically identical — so that the curve represented on the figure may be considered as being valid for all usual hole diameters.

The curve is traced for a very wide range of values of $\frac{R_t}{R_m}$, namely between 0.1 and 1,000. It is seen that when $\frac{R_t}{R_m}$ is less than about 300, the values of $\frac{R_a}{R_m}$ are equal to the corresponding values of $\frac{R_t}{R_m}$. When $\frac{R_t}{R_m}$ is greater than 300, the

values of $\frac{R_a}{R_m}$ are slightly higher, and the difference attains 20 per cent for $\frac{R_t}{R_m} = 1{,}000$.

The behavior of device *A* will now be examined for the case of an invaded bed. Fig. 8 relates to a bed of infinite thickness, traversed by a bore hole of diameter *d*, the diameter *Di** of the invaded zone being equal to 2*d*. The chart is intended to show how the response of the Laterolog varies according to whether the invaded zone is more or less resistive than the uncontaminated part of the bed. To this end, the ratio of the resistivity of the invaded zone R_i to the true resistivity of the bed R_t is born in abscissae, and the ratio of the apparent resistivity R_a to the true resistivity R_t is born in ordinates. The points plotted on this chart were also determined by computations.

For $\frac{R_i}{R_t}$ less than 1 (conductive muds, and, consequently, conductive mud filtrate), the average curve is very close to the horizontal line of ordinate 1; and for values of $\frac{R_i}{R_t}$ greater than 1 (fresh mud, and, consequently, fresh mud filtrate), the curve rises progressively. In other words, as long as R_i is less than R_t, the apparent resistivity is about equal to the true resistivity; when R_i is slightly greater than R_t, say less than twice as great as R_t, R_a is still close to R_t, but a little higher — the difference not exceeding 30 per cent; for greater values of $\frac{R_i}{R_t}$, R_a becomes much greater than R_t and attains a value of about 2 to 2.5 R_t when $\frac{R_i}{R_t}$ is equal to 10.

The conclusion of this analysis is that the Laterolog device gives values of resistivity which are practically not affected by the invaded zone, provided the resistivity of the invaded zone is not appreciably greater than the resistivity of the uncontaminated part of the bed. In the case of a formation of comparatively low porosity, the depth of invasion may be greater than 2*d*, and the influence of the invaded zone may be somewhat more important than is shown on the chart. The values of apparent resistivity are, nevertheless, still reasonably close to the true resistivity when R_i is greater than R_t.

It is clear that conditions favorable to the use of the Laterolog are obtained when the resistivity of the invaded zone and, accordingly, the resistivity of the mud, is low. Of course, it would not be advisable to decrease purposely the resistivity of the mud too much in order to improve the response of the Laterolog, because, for too low a mud resistivity, the SP curve is reduced to an almost flat line. But, in those regions where the mud is of high salinity anyway, because of the presence of a salt rock bed above the formations to be surveyed, the Laterolog finds automatically an excellent field of application, and more so because in that case all the conventional electric logs are either featureless or very much distorted.

Other combinations of electrodes are possible wherein the thickness of the sheet of current is taken smaller than with device A. One of these combinations corresponds to $O_1O_2 =$ 12 in. and $A_1A_2 = 72$ in. (device B). The response of this device, as calibrated for practical use, is shown on the computed chart of Fig. 9.

It is seen that with device B, when $\frac{R_t}{R_m}$ is greater than about 20, the values of $\frac{R_a}{R_m}$ are very close to the corresponding values of $\frac{R_t}{R_m}$, namely within a few per cent. When $\frac{R_t}{R_m}$ is less than 20, the values of $\frac{R_a}{R_m}$ are greater than $\frac{R_t}{R_m}$, and the less $\frac{R_t}{R_m}$, the greater the difference.

In the case of bore holes drilled with high salinity mud, and more generally, for holes drilled through hard formations, the ratio of formation resistivity to mud resistivity is almost always greater than 20, or at least greater than 10, so that the values of $\frac{R_a}{R_m}$ recorded opposite any non-invaded formation will fall in that part of the curve where $\frac{R_a}{R_m}$ is substantially equal to $\frac{R_t}{R_m}$.

Device B is therefore well adapted to the determination of true resistivities in wells drilled with high salinity mud, or in hard formations, and it has, furthermore, the advantage over

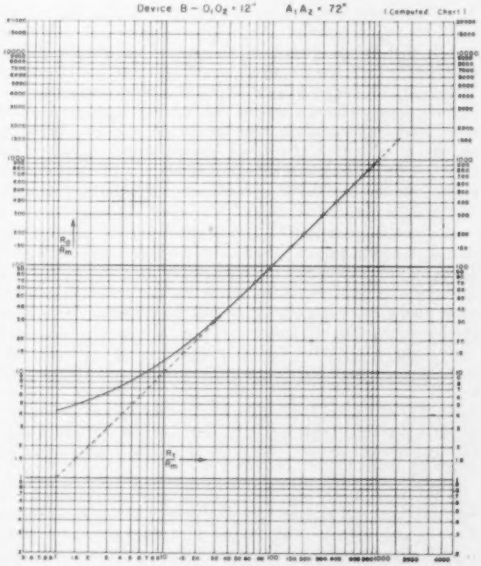

FIG. 9 — RESPONSE OF LATEROLOG DEVICE, HOMOGENEOUS BED OF INFINITE THICKNESS, NO INVASION.

*It is supposed, for the convenience of the discussion, that the invaded zone is equivalent to a homogeneous medium, bounded by two co-axial cylindrical surfaces of diameters *d* and *Di*. In fact, this representation is not entirely exact, and there is more likely a progressive change of resistivity between the invaded zone and the uncontaminated part of the bed.

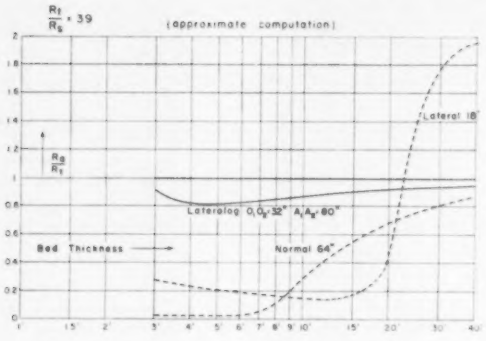

FIG. 10 — EFFECT OF BED THICKNESS ON THE RESPONSE OF THE LATEROLOG DEVICE AND THE CONVENTIONAL DEVICES, NO INVASION, HOLE NEGLECTED. R_t: RESISTIVITY OF BED. R_s: RESISTIVITY OF ADJACENT FORMATIONS. R_a: APPARENT RESISTIVITY.

device A that it makes possible the investigation of thinner beds, since the thickness of the current sheet is only equal to about 1 ft instead of about 3 ft.

Influence of Bed Thickness

The exact computation of the true resistivities recorded with a Laterolog device opposite a bed of finite thickness traversed by a bore hole does not seem to be possible in the present stage of our knowledge. The problem, therefore, has been, and is still being investigated by means of laboratory tests on models. Some of the results obtained thus far have been reproduced in Fig. 6, which illustrates the preceding section of this paper. Although quite a few laboratory determinations have already been made, the results are not yet numerous enough at present to provide a complete information on the effect of the bed thickness, but they show that this effect is small, provided the bed thickness is greater than the thickness of the sheet of current.

Approximate indications can furthermore be obtained by means of computations when the effect of the bore hole is neglected. Fig. 10 shows the results of such computations for the case of a bed, whose resistivity R_t has been taken equal to 39 times the resistivity R_s of the surrounding formations. On the figure, bed thicknesses, in feet, are born in abscissae, and the corresponding computed values of $\frac{R_a}{R_t}$ are in ordinates. Three curves are traced which correspond respectively to the Laterolog device ($O_1O_2 = 32$ in. and $A_1A_2 = 80$ in.) to the long normal device ($AM = 64$ in.), and to the lateral device ($AO = 18$ ft.).

If the bore hole were taken into consideration, the departure between the apparent resistivity and the true resistivity for thin beds with the normal and the lateral device would be greater than is shown on the chart, whereas, for the Laterolog device, the departure would be substantially the same.

Quite similar results are obtained for other values of $\frac{R_t}{R_s}$. The relative departure of R_a from R_t is, however, more important for a bed more conductive than the adjacent formations, but, in this case, further laboratory experiments are necessary to determine the exact response of the Laterolog device.

FIELD TECHNIQUE

Fig. 11a shows schematically the circuit generally used for recording the Laterolog curve. An AC current of constant intensity is fed through electrode A_o by means of a generator located at the surface. Electrodes M_1M_2 *and* $M'_1M'_2$ on the one hand, electrodes A_1A_2 and surface electrode B_1 on the other hand, are respectively connected to the input and output terminals of an automatic control apparatus (1). By means of this apparatus, a current is fed through A_1 and A_2 which continuously acts to maintain the difference of potential between M_1M_2 and $M'_1M'_2$ substantially equal to zero. The common potential of electrodes $M_1M_2M'_1M'_2$ is recorded by means of meter (2), with reference to an electrode N placed in the bore hole at a great distance from the measuring device.

The automatic control system used to keep the potential difference between M_1M_2 and $M'_1M'_2$ equal to zero can be applied equally well to another electrode arrangement as shown in Fig. 11b. In this case, instead of the point electrodes of the standard Laterolog, elongated electrodes are used, namely one central electrode A'_o and two symmetrical and

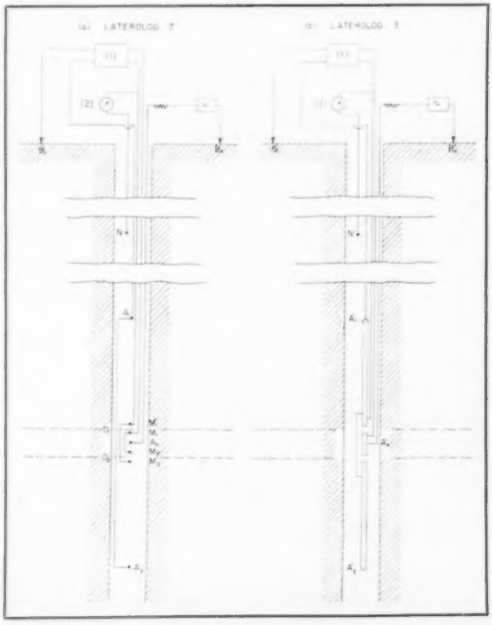

FIG. 11 — LATEROLOG — SCHEMATIC CIRCUITS.

short-circuited electrodes $A'_1A'_2$. The technique of measurement is essentially the same as that just described; a current of constant intensity is fed to electrode A'_0 and the difference of potential between A'_0 *and* $A'_1A'_2$ is maintained substantially nil by means of the same automatic control apparatus (1'). The common potential of $A'_0A'_1A'_2$ is recorded by means of meter (2). For the sake of differentiation, this system can be designated as "Laterolog 3" (3-electrode Laterolog), and the standard system as "Laterolog 7" (7-electrode Laterolog).

It appears that with Laterolog 3, the current is made to flow within a substantially horizontal sheet of space, whose thickness is about equal to the length of electrode A'_0. If the length of electrode A'_0 in Laterolog 3 is taken equal to the distance O_1O_2 in Laterolog 7, the thicknesses of the sheets of current in both cases will be the same, and both devices will have similar abilities for the detection of details.

The response of Laterolog 3 cannot be determined by computations — as is the case for the Laterolog with point electrodes — and must be investigated by laboratory experiments on scale models. Although such experiments are not yet sufficient to provide a complete answer, it seems possible to foresee that Laterolog 3 will give results substantially equivalent to those of Laterolog 7, provided its overall length is appreciably greater.

One important feature is that with Laterolog 3, the presence of a long metallic body in the bore hole affects the SP curve adversely. This fact, however, will present no practical drawback in the case of wells filled with high salinity mud, where the SP curve is reduced to a practically flat line anyway. It is reasonable to think that, in the case where the mud is not very salty, and where, therefore, the SP curve gives valuable indications, the use of Laterolog 7 will be preferable. Laterolog 7 has also the advantage that other resistivity logs with electrodes, or induction logs, can be recorded simultaneously without the fundamental difficulty that would result from the presence of a long metallic body.

FIELD EXAMPLES

Fig. 12 is an example of application of Laterolog 7 in the case of limestones drilled with a mud saturated with salt (West Texas). The figure also includes, for comparison, the resistivity curves recorded with the conventional device, and the SP curve — although this last curve is reduced to a straight line in this case.

One striking feature on the figure is the considerable difference in the amplitudes of the resistivities recorded with the various devices.

The resistivities recorded with the short normal and the limestone sonde are very low, not greater than about ten ohm-m, because the radii of investigation of these devices are small and the by-pass effect of the mud column is particularly important. In comparison, resistivities as high as 250 ohm-m are obtained with the lateral device, whose radius of investigation is very large, and also with the Laterolog device.

The Laterolog furthermore gives a sharp and detailed delineation of the beds. Some of these details correspond to slight excursions on the limestone sonde curve, which is reproduced on the right-hand track with an amplified resistivity scale. Many details clearly indicated on the Laterolog, however, are lacking on the limestone sonde curve, despite the enlarged scale.

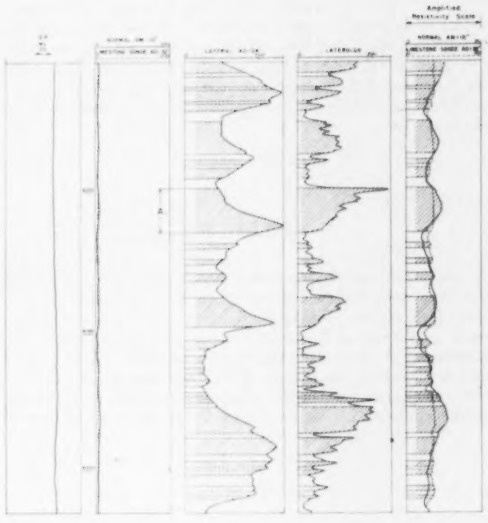

FIG. 12 — EXAMPLE OF LATEROLOG 7, HARD FORMATIONS, HIGH SALINITY MUD (WEST TEXAS). HOLE DIAMETER 7⅞ IN., MUD RESISTIVITY (CORRECTED FOR TEMP.): 0.04 OHM-M. SHADED AREAS ARE TRACED FROM THE LATEROLOG AND CORRESPOND TO THE BEDS WHICH ARE MORE RESISTIVE THAN ADJACENT FORMATIONS.

Although large contrasts of resistivities are observed both on the lateral curve and on the Laterolog, the shapes of the two curves are markedly different. As proven by theoretical and laboratory studies, the Laterolog gives an exact record of the formations, and can be taken as a reference log. The comparison between the lateral curve and the Laterolog curve shows clearly therefore how much the former is distorted by the effect of the mud column, although it gives approximately the value of the average resistivity over large sections of formation. If interval (A) is considered, for example, it appears from the Laterolog curve that the resistivity actually decreases from the top to the bottom. On the lateral curve, a "blind zone" is noticed below the upper boundary, and a maximum is attained near the lower boundary, which gives the erroneous impression that the resistivity increases downward.

Fig. 13 is another example of Laterolog 7 in hard formations drilled with high salinity mud (Kansas). Quite similar remarks can be made regarding this example.

Fig. 14 is a comparative example showing curves recorded with Laterolog 7 and Laterolog 3 in high resistivity formations (Kansas). In this well both Laterologs were recorded in comparatively conductive mud (resistivity, corrected for temperature = 0.2 ohm-m). The conventional logs were recorded after the salt mud had been replaced by fresh mud (resistivity: corrected for temperature, 1.7 ohm-m). In this example, the thicknesses of the beams were respectively 6 in. and 12 in. for the Laterolog 3 and the Laterolog 7, and the overall lengths of both sondes were substantially equal. A few minor details, which are indicated by the Laterolog 3, do not appear as

clearly on the curve with the Laterolog 7: these details correspond to thin beds, whose thickness is below 12 in. On the other hand, those thin beds which are more than 12 in. thick give rise to a sharper contrast with the Laterolog 7 than with the Laterolog 3, because in this particular instance the focusing properties of the former system are better than those of the latter one.

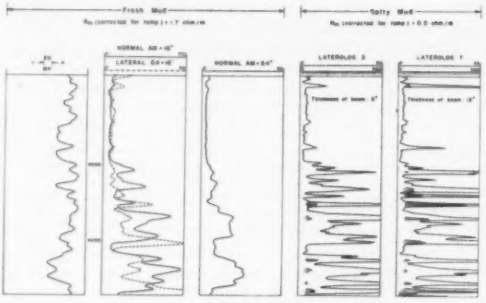

FIG. 14 — COMPARATIVE EXAMPLE OF LATEROLOG 3 AND LATEROLOG 7 IN HARD FORMATIONS (KANSAS).

CONCLUSION

A new method for the measurement of resistivity in bore holes has been described, which involves a controlled focusing system of electrodes, whereby the current used for the measurement is obliged to flow within a narrow slice of space, the boundaries of which are substantially horizontal up to a great distance from the bore hole. With this method, the effect of the mud column, and of the adjacent formations on the value of the apparent resistivity measured opposite a given bed is practically eliminated, wherever the thickness of the bed is at least equal to the thickness of the sheet of current, *i.e.*, a few inches to a few feet, depending on the distances between the electrodes.

By means of the Laterolog an accurate and detailed delineation of formations is obtained. The new method furthermore gives values of apparent resistivity which are close to the true values, provided the depth of invasion of mud filtrate is not too deep, and provided the resistivity of the invaded zone is not greater than the resistivity of the uncontaminated part of the bed under survey. This last condition is frequently satisfied in the case of oil-bearing beds, particularly when the salinity of the mud is not much lower than the salinity of the connate water.

Because of its remarkable ability to overcome the by-pass effect of the mud column, the Laterolog has been first introduced in those regions where this effect is particularly detrimental for conventional electrical logs, *i.e.*, where high salinity muds are commonly used. The usefulness of the Laterolog, however, is not limited to this case, but, on the contrary, should extend at least to all hard formation territories.

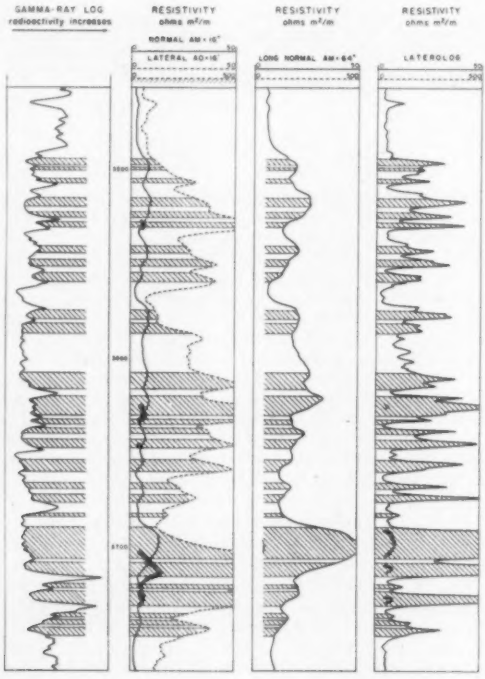

FIG. 13 — EXAMPLE OF LATEROLOG 7, HARD FORMATIONS, HIGH SALINITY MUD (KANSAS). HOLE DIAMETER 7⅞ IN., MUD RESISTIVITY (CORRECTED FOR TEMP.): 0.07 OHM-M. SHADED AREAS ARE TRACED FROM THE LATEROLOG AND CORRESPOND TO THE BEDS WHICH ARE MORE RESISTIVE THAN THE ADJACENT FORMATIONS.

ACKNOWLEDGMENT

The author wishes to express his appreciation to the numerous engineers of the SWSC who cooperated in the development of the method, both at headquarters and in the field. Special acknowledgment is due to J. Bricaud, who was instrumental in designing the equipment and in conducting the experiments, and to A. Poupon, for his cooperation in the computation of the theoretical charts. The author also wishes to acknowledge the courtesy of the oil companies which provided bore holes for the experiments and which made examples available for the illustrations of this paper.

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5. Doll, H. G., and Martin, M.: "Recent Developments in Electrical Logging and Auxiliary Methods," *Quarterly of the Colorado School of Mines* (October, 1950) **45**, No. 4A, 48.
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DISCUSSION

By B. F. Howell, Jr., Pennsylvania State College, State College, Pa.

The need for a commercially available service offering this logging method has been apparent for some time. It is not a new technique. Similar, though somewhat different, ideas are described in U. S. Patents No. 2,446,303 and No. 2,347,794. The technique described in this paper was developed independently several years ago by the Pennsylvania State College Mineral Industries Experiment Station in cooperation with the Pennsylvania Grade Crude Oil Association, and has been in use by them in making electric logs as a part of their geophysical research program in the Bradford Field of Pennsylvania since 1949. Two preliminary papers by George V. Keller of Pennsylvania State College have been published describing the technique,* and a final report on its theory, applications and limitations will be published soon.

The method is particularly adapted to fields where beds are very thin. In such cases, it appears to give more detailed and more accurate measurements than any other logging system known. It is of particular value where the electric logs are to be used for quantitative calculations of reservoir properties. In the experience of this laboratory it is the only logging method which can be used dependably for this purpose where bed thicknesses are less than one ft.

AUTHOR'S REPLY TO MR. HOWELL

I agree with Howell that the technique of measuring formation resistivities in a bore hole by means of a focused sheet of current is not new. But I wish to remark that the system which constitutes the essential subject of the paper is the Laterolog with point electrodes and automatic control (called Laterolog 7), whereas any previous work, to my knowledge, is related to systems involving elongated electrodes. The use of point electrodes has the advantage of making possible the simultaneous recording of an accurate SP curve — assuming, of course, that there are SP's available, which is not true in high salinity mud — and also of other resistivity curves. Such recording would be particularly difficult to make in the case of a system with elongated electrodes.

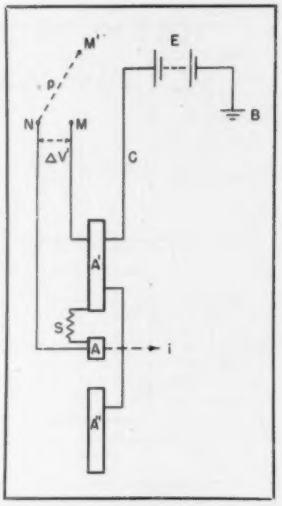

FIG. A — SCHEMATIC CIRCUIT OF GUARDED ELECTRODE AFTER C. SCHLUMBERGER'S DRAWING ON HIS MEMORANDUM OF OCT. 13, 1927.

I would say that I do not know of any reference of other work regarding the Laterolog with point electrodes. As for the use of elongated electrodes, this technique was invented by C. Schlumberger a long time ago, as mentioned in the introduction of my paper, and made public in 1940-41, during a litigation.

At that time, the matter was discussed at length, and, among other documents, the following information was disclosed:

1. A memorandum from C. Schlumberger dated Oct. 13, 1927.* This memorandum first contains a description of a system for measuring the formation resistivity in a bore hole by means of a monoelectrode. Then, the guarded electrode is described, as quoted hereafter:

> "If the formations considered are assumed to be formed of relatively thin horizontal layers, it is necessary to add two end electrodes *A'* and *A''* to the earth connection *A*, of substantially the same potential as *A*, and which force the lines of current leaving *A* to follow a horizontal path, corresponding to a cylindrical distribution of the potentials. The operation will be carried out as shown on the sketch, the current being led by the cable *C* and the shunt *S* being placed between *A* and *A'*."

Fig. A shows a schematic circuit redrawn from the original drawing made by C. Schlumberger on the hand-written copy of the said memorandum.

2. A log which I recorded in December, 1927, and concerning which I gave some information as follows:**

> " . . . We tried a slight improvement in the method with one electrode in the case of thin layers, by adding to the monoelectrode two guard rings, in accordance with Mr. Schlumberger's memorandum . . . This device was, in par-

*Keller, G. V.: "An Improved Electrode System for Use in Electric Logging," *Producers Monthly* (August, 1949); and "Modified Mono-Electrodes for Improved Resistivity Logging," *Producers Monthly* (July, 1950), also published in the proceedings of the Twelfth Technical Conference on Petroleum Production, Pennsylvania State College Mineral Industries Experiment Station Bulletin No. 54.

*U. S. Circuit Court of Appeals — Fifth Circuit — Transcript of Record No. 10063, Halliburton Oil Well Cementing Co. vs Sch'umberger Well Surveying Corp., 5, 3396.

**Ibid.* 3335.

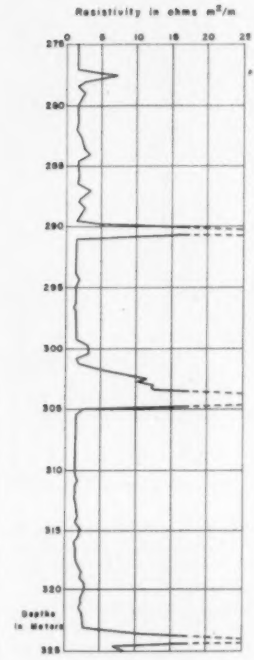

FIG. 8—RESISTIVITY LOG WITH GUARDED ELECTRODE IN WELL LOBSANN NO. 47, PECHELBRONN, FRANCE, DEC. 12, 1927.

ticular, tested by me in the Lobsann drill hole, derrick 47, on Dec. 12, 1927, as this drill hole had interesting thin layers (gypsum layers) . . ."

A copy of this log is given in Fig. B.

The device described in the present paper, under the name of Laterolog 3, is an improvement over the guarded electrode, characterized by the fact that it involves the same automatic control system as the Laterolog 7.

Finally, I would add that I am very glad to make references to the interesting articles published by G. V. Keller in the *Producers Monthly* issues of August, 1949, and July, 1950.

DISCUSSION

By Ray L. Braeutigam, Sinclair Oil and Gas Co., Tulsa, Okla., Member AIME

I should like to extend my congratulations to Doll and his associates on their splendid work on this paper — and the Laterolog. Frankly, my curiosity is aroused. From the examples presented in this paper, and from a few actual logs I have observed I think it can be seen that the Laterolog is capable of great detail in recording electrical responses and at the same time considerable depth penetration can be obtained. There is also evidence that bore hole effects can be eliminated to a large extent. Anyone engaged in detail studies of electric logs will welcome this group of desirable characteristics. All in all the prospects seem good for overcoming many of the problems which confront us when analyzing the regular electric logs. It is not too difficult to foresee the possibilities that this Laterolog may become a curve of major importance for both qualitative and quantitative reservoir analysis from the electric log. True, more work remains to be done, but the present outlook gives us good reason to set our expectations rather high.

The apparent resistivities, R_a, which this curve records are primarily R_1 plus R_t. It is indicated here that the conversion from R_a to R_t in many cases will be more easily accomplished than is now possible through the standard, or present electric logs. I think it would also be well to emphasize that by varying the $\frac{A_1 \text{ to } A_2}{O_1 \text{ to } O_2}$ spacing ratios, differences in depth penetration can be accomplished. This presents us with another possibility — the recording of two of these curves employing two different spacing ratios to give us R_1 to R_t. An accomplishment of this nature could greatly simplify quantitative interpretations from the electric log. After certain recording technique problems are solved, it may even be possible to record these two curves simultaneously.

I feel sure that the oil industry will welcome any further information on the Laterolog, as soon as Doll is prepared to offer it.

DISCUSSION

By M. R. J. Wyllie, Gulf Research and Development Co., Pittsburgh, Pa., Member AIME

Doll is to be congratulated upon the successful development of a logging device which has already done much to dispel the difficulties of logging in highly saline muds and which also contributes so signally to overcoming the thin bed problem. The device is presently not suited to the determination of the true resistivity of permeable conductive beds, but the running of a Laterolog and an induction log should theoretically give rise to sufficient equations to enable even this problem to be overcome. This assumes that some estimate of the depth of mud filtrate invasion can be made.

I should like to ask Doll if he can estimate the extent of the radial investigation of a Laterolog in homogeneous resistant beds. Possibly the radial distance into the formation which contributes 90 per cent of the observed resistivity, as a function of the Laterolog "spacing," might be a suitable way of expressing this result.

AUTHOR'S REPLY TO MESSRS. WYLLIE AND BRAEUTIGAM

I wish to thank Wyllie and Braeutigam for their interesting comments.

I would point out that the extent of the radial investigation of a Laterolog is mostly a function of the overall length of the electrode system. For the Laterolog 7 and in the case of homogeneous formation, the computations show that 90 per cent of the potential drop between the wall of the hole and infinity is obtained within a distance from the axis of the hole which is about three times the length A_1A_2. This result is no longer correct in the case of thin beds, more resistive than the adjacent formations, because, in this case, the sheet of current opens at a shorter distance from the hole than in the case of a very thick formation. This question of the investigation of thin beds with the Laterolog is the subject of intensive laboratory research at the present time.

It is right that the Laterolog is not well suited to the determination of the true resistivity of permeable conductive beds, it being the case, however, only when the resistivity of the bed is appreciably less than the resistivity of the invaded zone. As remarked by both writers, an improvement in the investigation of true resistivity should come from the combination of two resistivity measuring devices with different responses — as for example two Laterologs with different distributions of electrodes, or preferably one Laterolog combined with induction logging. ★ ★ ★

THE CALCULATION OF PRESSURE DROP IN THE FLOW OF NATURAL GAS THROUGH PIPE

FRED H. POETTMANN, PHILLIPS PETROLEUM CO., BARTLESVILLE, OKLA., JUNIOR MEMBER AIME

ABSTRACT

An equation has been derived for use in calculating the sandface pressure of flowing gas wells in which the variation of the compressibility factor of the gas with pressure is taken into consideration. This variation due to compressibility has been put into both graphical and tabular form. Comparison of calculated results with field measured results were made on 20 dry gas wells from a given field and 11 distillate wells from different fields. The agreement between calculated and observed results is good.

In addition to their use in the calculation of sandface pressures of flowing wells, the factors can be used in the direct calculation of the static bottom hole pressure of gas wells, the capacity of gas transmission lines, and in the calculation of the theoretical isothermal horsepower necessary to compress a natural gas. Examples demonstrating the use of various equations are given.

INTRODUCTION

Many of the equations used to calculate the sandface pressures of flowing gas wells from well head data do not take into consideration rigorously the deviation of the natural gas from ideal gas behavior. For low pressure wells this error is not serious. For high pressure wells flowing at high rates this error can be serious. Sandface pressures are used to determine the producing capacity of gas wells as shown in the U. S. Bureau of Mines' Monograph 7.[1]

An equation has been derived for use in calculating the sandface pressure of flowing gas wells in which the variation of compressibility of the gas with pressure is taken into consideration. This variation due to compressibility has been put into both graphical and tabular form. In addition to their use in the calculation of sandface pressures, these "factors" can also be used to give a direct solution in the calculation of the static bottom hole pressure of gas wells, the calculation of the capacity of gas transmission lines, and the calculation of the isothermal horsepower necessary to compress a gas.

CALCULATION OF SANDFACE PRESSURE OF FLOWING GAS WELLS

The starting point in the derivation of any specific flow equation is an energy balance on the fluid flowing between any two points in the system. This energy balance based on one pound of flowing fluid is expressed by the well known general flow equation:

$$\int_{P_1}^{P_2} V dP + \triangle h + \frac{\triangle v^2}{2 g_c} + W_f + W_s = 0 \quad . . \quad (1)$$

where

V = specific volume of flowing fluid in cu ft/lb
P = pressure in lb per sq ft
$\triangle h$ = difference in height above datum plane in ft
$\frac{\triangle v_2}{2 g_c}$ = kinetic energy change of one lb of flowing fluid, v equals velocity in ft/sec and $g_c = 32.174$
W_s = Work done by fluid while in flow (similar to shaft work in driving a turbine)
W_f = Energy losses due to the irreversibilities of the flowing fluid

This equation contains no limiting assumptions and can be made the basis of any fluid flow relationship by limitations or substitutions. The energy units are usually expressed in terms of foot-pounds of energy per pound of mass.

Considering the vertical flow of gas through tubing or annulus, the external work W_s done by the gas is zero. Let us also assume that the value of the kinetic energy function is small and can be neglected. Equation (1) is reduced to:

$$\int_{P_1}^{P_2} V dP + \triangle h + W_f = 0 \quad . . . . . \quad (2)$$

The energy losses W_f can be expressed in terms of the well known Fanning equation:

$$W_f = \frac{4 f L \bar{v}^2}{2 g_c D} \quad . . . . . \quad (3)$$

where

L = the integrated average velocity in ft/sec of vertical flow in a uniform flow string $\triangle h = L$
$\bar{v}$ = the integrated average velocity in ft/sec
f = dimensionless correlating function

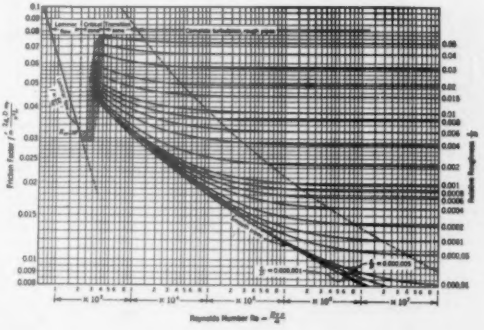

FIG. 1 — FRICTION FACTOR AS A FUNCTION OF REYNOLDS NUMBER WITH RELATIVE ROUGHNESS AS A PARAMETER.[6]

[1]References given at end of paper.

Manuscript received in the office of the Petroleum Branch May 23, 1951. Paper presented at the Fall Meeting of the Petroleum Branch in Oklahoma City, Okla., Oct. 3-5, 1951.

Values of f are correlated as functions of the Reynolds number $\frac{Dpv}{\mu}$ and relative roughness $\frac{\epsilon}{D}$. Care must be taken to avoid confusion as quite often a multiple of four times f is plotted as a function of the Reynolds number and relative roughness ($f' = 4f$).[2]

Substituting Equation (3) in Equation (2) and simplifying gives:

$$L = \frac{\int_{P_2}^{P_1} V dP}{1 + \frac{4 f \bar{v}^2}{2 g_c D}} \quad \ldots \ldots \ldots \ldots \quad (4)$$

The specific volume V can be expressed in terms of the gas law:

$$V = \frac{ZRT}{MP} \quad \ldots \ldots \ldots \ldots \quad (5)$$

Where

Z = Compressibility factor
R = Gas constant 1544
T = Temperature °R
M = Molecular weight of gas
P = Pressure, lb/sq ft

Then:

$$\int_{P_2}^{P_1} V dP = \frac{RT}{M} \int_{P_2}^{P_1} \frac{Z}{P} dP \quad \ldots \ldots \quad (6)$$

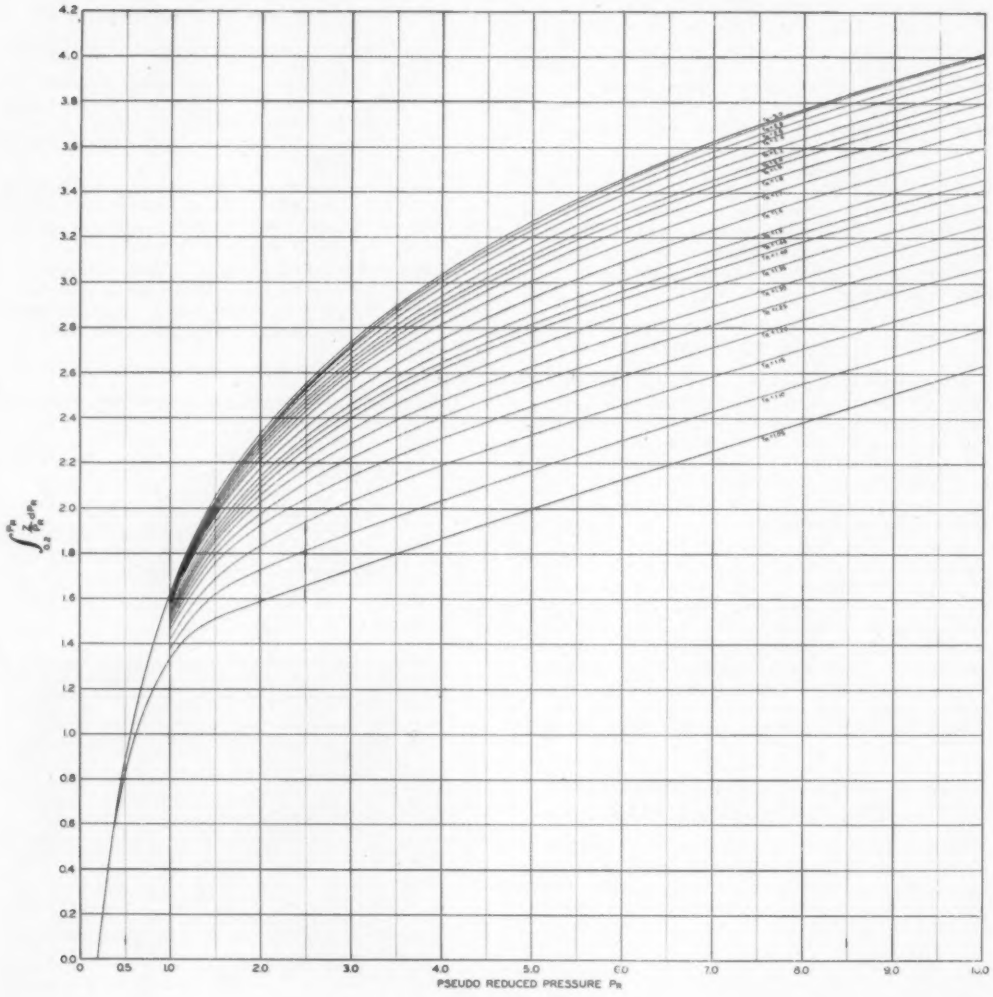

FIG. 2 — VARIATION OF $\int_{0.2}^{P_r} \frac{Z}{P_r} dP_r$ WITH P_r.

Table I

Values of $\int_{0.2}^{P_r} \frac{z}{P_r}\, dP_r$

Pseudo Reduced Pressure P_r	Pseudo Reduced Temperature T_r 1.05	1.10	1.15	1.20	1.25	1.30	1.35
0.2	0	0	0	0	0	0	0
0.3	0.350	0.350	0.350	0.350	0.350	0.350	0.350
0.4	0.615	0.619	0.623	0.626	0.628	0.630	0.632
0.5	0.805	0.816	0.826	0.834	0.839	0.844	0.848
0.6	0.955	0.971	0.985	0.998	1.011	1.022	1.032
0.7	1.078	1.100	1.124	1.145	1.162	1.178	1.190
0.8	1.175	1.207	1.239	1.264	1.285	1.300	1.313
0.9	1.256	1.300	1.335	1.365	1.386	1.403	1.417
1.0	1.327	1.375	1.420	1.455	1.479	1.500	1.415
1.1	1.380	1.438	1.435	1.528	1.552	1.573	1.591
1.2	1.433	1.500	1.550	1.600	1.625	1.645	1.666
1.3	1.463	1.545	1.602	1.657	1.684	1.709	1.731
1.4	1.492	1.590	1.654	1.713	1.742	1.772	1.795
1.5	1.510	1.620	1.690	1.757	1.791	1.824	1.848
1.6	1.527	1.649	1.726	1.800	1.839	1.875	1.900
1.7	1.544	1.670	1.754	1.834	1.876	1.917	1.943
1.8	1.560	1.690	1.782	1.867	1.913	1.958	1.985
1.9	1.575	1.708	1.808	1.896	1.944	1.993	2.022
2.0	1.590	1.725	1.833	1.924	1.975	2.027	2.059
2.1	1.604	1.743	1.854	1.947	2.003	2.057	2.092
2.2	1.617	1.761	1.876	1.971	2.031	2.086	2.125
2.3	1.631	1.779	1.897	1.994	2.059	2.116	2.157
2.4	1.644	1.797	1.919	2.018	2.087	2.145	2.190
2.5	1.658	1.815	1.940	2.041	2.115	2.175	2.223
2.6	1.672	1.830	1.958	2.061	2.137	2.198	2.249
2.7	1.685	1.845	1.976	2.081	2.159	2.221	2.275
2.8	1.699	1.860	1.994	2.101	2.180	2.245	2.302
2.9	1.712	1.875	2.012	2.121	2.202	2.268	2.328
3.0	1.726	1.890	2.030	2.140	2.224	2.291	2.354
3.1	1.740	1.904	2.046	2.157	2.243	2.311	2.376
3.2	1.754	1.918	2.062	2.175	2.261	2.331	2.397
3.3	1.767	1.932	2.078	2.192	2.280	2.350	2.419
3.4	1.781	1.946	2.094	2.210	2.298	2.370	2.440
3.5	1.795	1.960	2.110	2.227	2.317	2.390	2.462
3.6	1.808	1.974	2.125	2.243	2.333	2.407	2.480
3.7	1.822	1.988	2.140	2.259	2.349	2.424	2.498
3.8	1.835	2.002	2.155	2.275	2.365	2.440	2.517
3.9	1.849	2.016	2.170	2.291	2.381	2.457	2.535
4.0	1.862	2.030	2.186	2.306	2.397	2.474	2.553
4.1	1.875	2.044	2.201	2.321	2.413	2.490	2.569
4.2	1.889	2.058	2.216	2.336	2.429	2.506	2.586
4.3	1.902	2.073	2.230	2.351	2.444	2.523	2.602
4.4	1.916	2.087	2.245	2.366	2.460	2.539	2.619
4.5	1.929	2.101	2.260	2.381	2.476	2.555	2.635
4.6	1.942	2.115	2.274	2.395	2.491	2.570	2.651
4.7	1.955	2.128	2.288	2.409	2.507	2.586	2.666
4.8	1.969	2.142	2.301	2.423	2.522	2.601	2.682
4.9	1.982	2.155	2.315	2.437	2.538	2.617	2.697
5.0	1.995	2.169	2.329	2.451	2.553	2.632	2.713
5.1	2.009	2.183	2.342	2.465	2.567	2.646	2.728
5.2	2.024	2.197	2.355	2.479	2.581	2.661	2.743
5.3	2.038	2.210	2.369	2.492	2.595	2.675	2.758
5.4	2.053	2.224	2.382	2.506	2.609	2.690	2.773
5.5	2.067	2.238	2.395	2.520	2.623	2.704	2.788
5.6	2.079	2.251	2.408	2.533	2.636	2.718	2.801
5.7	2.091	2.264	2.421	2.547	2.650	2.731	2.815
5.8	2.102	2.277	2.435	2.560	2.663	2.745	2.828
5.9	2.114	2.290	2.448	2.574	2.677	2.758	2.842
6.0	2.126	2.303	2.461	2.587	2.690	2.772	2.855
6.1	2.139	2.316	2.474	2.600	2.703	2.785	2.869
6.2	2.152	2.328	2.486	2.612	2.716	2.799	2.882
6.3	2.165	2.341	2.499	2.625	2.729	2.812	2.896
6.4	2.178	2.353	2.511	2.637	2.742	2.826	2.909
6.5	2.191	2.366	2.524	2.650	2.755	2.839	2.923
6.6	2.204	2.379	2.536	2.662	2.768	2.852	2.936
6.7	2.217	2.391	2.548	2.675	2.781	2.864	2.949
6.8	2.229	2.404	2.560	2.687	2.794	2.877	2.963
6.9	2.242	2.416	2.572	2.700	2.807	2.889	2.976
7.0	2.255	2.429	2.584	2.712	2.820	2.902	2.989
7.1	2.268	2.442	2.597	2.724	2.832	2.915	3.002
7.2	2.281	2.454	2.609	2.737	2.844	2.928	3.014
7.3	2.294	2.467	2.622	2.749	2.856	2.941	3.027
7.4	2.307	2.479	2.634	2.762	2.868	2.954	3.039
7.5	2.320	2.492	2.647	2.774	2.880	2.967	3.052
7.6	2.333	2.505	2.660	2.786	2.892	2.979	3.065
7.7	2.346	2.517	2.672	2.799	2.904	2.991	3.077
7.8	2.359	2.530	2.685	2.811	2.916	3.003	3.090
7.9	2.372	2.542	2.697	2.824	2.928	3.015	3.102
8.0	2.385	2.555	2.710	2.836	2.940	3.027	3.115
8.1	2.398	2.568	2.723	2.848	2.952	3.039	3.127
8.2	2.411	2.580	2.736	2.861	2.964	3.051	3.139
8.3	2.424	2.593	2.748	2.873	2.977	3.064	3.151
8.4	2.437	2.605	2.761	2.886	2.989	3.076	3.163
8.5	2.450	2.618	2.774	2.898	3.001	3.088	3.175
8.6	2.462	2.631	2.787	2.910	3.013	3.100	3.187
8.7	2.475	2.643	2.799	2.923	3.025	3.112	3.199
8.8	2.487	2.656	2.812	2.935	3.038	3.124	3.211
8.9	2.500	2.668	2.824	2.948	3.050	3.136	3.223
9.0	2.512	2.681	2.837	2.960	3.062	3.148	3.235

Pseudo Reduced Pressure P_r	Pseudo Reduced Temperature T_r 1.05	1.10	1.15	1.20	1.25	1.30	1.35
9.1	2.524	2.693	2.849	2.972	3.074	3.159	3.246
9.2	2.536	2.706	2.861	2.985	3.085	3.170	3.257
9.3	2.549	2.718	2.872	2.997	3.097	3.182	3.268
9.4	2.561	2.731	2.884	3.010	3.108	3.193	3.279
9.5	2.573	2.743	2.896	3.022	3.120	3.204	3.290
9.6	2.585	2.755	2.908	3.034	3.131	3.216	3.302
9.7	2.597	2.767	2.919	3.045	3.142	3.228	3.314
9.8	2.610	2.780	2.931	3.057	3.153	3.239	3.326
9.9	2.622	2.792	2.942	3.068	3.164	3.251	3.338
10.0	2.634	2.804	2.954	3.080	3.175	3.263	3.350
10.1	2.646	2.816	2.966	3.092	3.187	3.274	3.361
10.2	2.658	2.828	2.978	3.103	3.199	3.286	3.372
10.3	2.671	2.840	2.989	3.115	3.211	3.297	3.382
10.4	2.683	2.852	3.001	3.126	3.223	3.309	3.393
10.5	2.695	2.864	3.013	3.138	3.235	3.320	3.404
10.6	2.707	2.876	3.025	3.150	3.246	3.332	3.416
10.7	2.719	2.888	3.037	3.161	3.258	3.343	3.428
10.8	2.732	2.900	3.048	3.173	3.269	3.355	3.440
10.9	2.744	2.912	3.060	3.184	3.281	3.366	3.452
11.0	2.756	2.924	3.072	3.196	3.292	3.378	3.464
11.1	2.768	2.936	3.084	3.208	3.304	3.389	3.475
11.2	2.780	2.948	3.096	3.220	3.315	3.401	3.486
11.3	2.793	2.960	3.108	3.231	3.327	3.412	3.497
11.4	2.805	2.972	3.120	3.243	3.338	3.424	3.508
11.5	2.817	2.984	3.132	3.255	3.350	3.435	3.519
11.6	2.829	2.996	3.144	3.267	3.361	3.446	3.529
11.7	2.841	3.008	3.156	3.279	3.373	3.456	3.540
11.8	2.854	3.020	3.168	3.290	3.384	3.467	3.550
11.9	2.866	3.032	3.180	3.302	3.396	3.477	3.561
12.0	2.878	3.044	3.192	3.314	3.407	3.488	3.571

Pseudo Reduced Pressure P_r	Pseudo Reduced Temperature T_r 1.40	1.45	1.50	1.60	1.70	1.80	1.90
0.2	0	0	0	0	0	0	0
0.3	0.350	0.350	0.350	0.350	0.350	0.350	0.350
0.4	0.633	0.634	0.635	0.636	0.637	0.638	0.639
0.5	0.851	0.854	0.856	0.860	0.862	0.864	0.866
0.6	1.040	1.045	1.048	1.049	1.049	1.050	1.050
0.7	1.199	1.203	1.207	1.210	1.211	1.213	1.214
0.8	1.322	1.332	1.340	1.347	1.352	1.357	1.359
0.9	1.429	1.440	1.450	1.462	1.472	1.480	1.485
1.0	1.530	1.541	1.551	1.568	1.580	1.590	1.598
1.1	1.606	1.616	1.631	1.653	1.667	1.676	1.684
1.2	1.682	1.690	1.710	1.737	1.753	1.761	1.770
1.3	1.746	1.758	1.779	1.810	1.828	1.836	1.845
1.4	1.810	1.825	1.847	1.882	1.903	1.911	1.920
1.5	1.867	1.884	1.906	1.938	1.962	1.973	1.984
1.6	1.923	1.943	1.964	1.993	2.021	2.035	2.047
1.7	1.969	1.991	2.012	2.043	2.072	2.089	2.102
1.8	2.014	2.038	2.060	2.093	2.123	2.142	2.157
1.9	2.054	2.079	2.100	2.136	2.165	2.187	2.204
2.0	2.093	2.119	2.140	2.178	2.207	2.231	2.250
2.1	2.126	2.153	2.176	2.215	2.248	2.272	2.292
2.2	2.160	2.187	2.212	2.252	2.288	2.313	2.334
2.3	2.193	2.222	2.249	2.288	2.329	2.354	2.375
2.4	2.227	2.256	2.285	2.325	2.369	2.395	2.417
2.5	2.260	2.290	2.321	2.362	2.410	2.436	2.459
2.6	2.288	2.318	2.350	2.392	2.442	2.469	2.492
2.7	2.316	2.347	2.379	2.423	2.474	2.502	2.525
2.8	2.344	2.375	2.407	2.453	2.506	2.534	2.557
2.9	2.372	2.404	2.436	2.484	2.538	2.567	2.590
3.0	2.400	2.432	2.465	2.514	2.570	2.600	2.623
3.1	2.423	2.455	2.489	2.540	2.597	2.628	2.652
3.2	2.446	2.478	2.512	2.565	2.623	2.657	2.681
3.3	2.469	2.502	2.536	2.591	2.650	2.685	2.709
3.4	2.492	2.525	2.559	2.616	2.676	2.714	2.738
3.5	2.515	2.548	2.583	2.642	2.703	2.742	2.767
3.6	2.535	2.568	2.603	2.664	2.726	2.766	2.792
3.7	2.556	2.588	2.624	2.686	2.748	2.791	2.817
3.8	2.576	2.609	2.644	2.708	2.771	2.815	2.843
3.9	2.597	2.629	2.665	2.730	2.793	2.840	2.868
4.0	2.617	2.649	2.685	2.752	2.816	2.864	2.893
4.1	2.634	2.667	2.703	2.771	2.836	2.885	2.915
4.2	2.651	2.685	2.721	2.789	2.856	2.907	2.937
4.3	2.669	2.702	2.740	2.808	2.875	2.928	2.958
4.4	2.686	2.720	2.758	2.826	2.895	2.950	2.980
4.5	2.703	2.738	2.776	2.845	2.915	2.971	3.002
4.6	2.719	2.754	2.793	2.863	2.933	2.990	3.022
4.7	2.735	2.770	2.810	2.881	2.952	3.009	3.041
4.8	2.752	2.786	2.826	2.899	2.970	3.027	3.061
4.9	2.768	2.802	2.843	2.917	2.989	3.046	3.080
5.0	2.784	2.818	2.860	2.935	3.007	3.065	3.100
5.1	2.799	2.834	2.876	2.952	3.024	3.082	3.118
5.2	2.814	2.850	2.892	2.968	3.042	3.099	3.136
5.3	2.830	2.865	2.908	2.985	3.059	3.117	3.153
5.4	2.845	2.881	2.924	3.001	3.077	3.134	3.171
5.5	2.860	2.897	2.940	3.018	3.094	3.151	3.189

Table I (Continued)

Pseudo Reduced Pressure P_r	Pseudo Reduced Temperature T_r 1.40	1.45	1.50	1.60	1.70	1.80	1.90
5.6	2.874	2.912	2.955	3.037	3.110	3.168	3.206
5.7	2.888	2.926	2.970	3.049	3.125	3.185	3.224
5.8	2.902	2.941	2.985	3.065	3.141	3.201	3.241
5.9	2.916	2.955	3.000	3.080	3.156	3.218	3.259
6.0	2.930	2.970	3.015	3.096	3.172	3.235	3.276
6.1	2.943	2.984	3.029	3.111	3.187	3.250	3.292
6.2	2.956	2.997	3.043	3.125	3.202	3.266	3.308
6.3	2.970	3.011	3.056	3.140	3.218	3.281	3.323
6.4	2.983	3.024	3.070	3.154	3.233	3.297	3.339
6.5	2.996	3.038	3.084	3.169	3.248	3.312	3.355
6.6	3.009	3.051	3.098	3.183	3.262	3.327	3.370
6.7	3.022	3.064	3.112	3.197	3.276	3.341	3.385
6.8	3.034	3.077	3.126	3.210	3.291	3.356	3.399
6.9	3.047	3.090	3.140	3.224	3.305	3.370	3.414
7.0	3.060	3.103	3.154	3.238	3.319	3.385	3.429
7.1	3.073	3.116	3.167	3.251	3.332	3.399	3.443
7.2	3.085	3.129	3.180	3.264	3.345	3.413	3.457
7.3	3.098	3.141	3.194	3.278	3.359	3.427	3.472
7.4	3.110	3.154	3.207	3.291	3.372	3.441	3.486
7.5	3.123	3.167	3.220	3.304	3.385	3.455	3.500
7.6	3.135	3.180	3.233	3.317	3.398	3.468	3.514
7.7	3.147	3.192	3.246	3.330	3.411	3.482	3.528
7.8	3.160	3.205	3.260	3.344	3.424	3.495	3.541
7.9	3.172	3.217	3.274	3.357	3.437	3.509	3.555
8.0	3.184	3.230	3.287	3.370	3.450	3.522	3.569
8.1	3.197	3.242	3.299	3.382	3.462	3.534	3.581
8.2	3.209	3.254	3.311	3.394	3.474	3.546	3.594
8.3	3.222	3.266	3.323	3.407	3.486	3.559	3.606
8.4	3.234	3.278	3.335	3.419	3.498	3.571	3.619
8.5	3.247	3.290	3.347	3.431	3.510	3.583	3.631
8.6	3.259	3.302	3.359	3.443	3.523	3.595	3.643
8.7	3.270	3.315	3.370	3.456	3.535	3.607	3.655
8.8	3.283	3.327	3.382	3.468	3.548	3.619	3.666
8.9	3.293	3.340	3.393	3.481	3.560	3.631	3.678
9.0	3.305	3.352	3.405	3.493	3.573	3.643	3.690
9.1	3.317	3.364	3.417	3.505	3.585	3.655	3.702
9.2	3.329	3.376	3.429	3.517	3.597	3.667	3.714
9.3	3.340	3.388	3.440	3.530	3.608	3.678	3.725
9.4	3.352	3.400	3.452	3.542	3.620	3.690	3.737
9.5	3.364	3.412	3.464	3.554	3.632	3.702	3.749
9.6	3.376	3.424	3.475	3.565	3.644	3.713	3.760
9.7	3.388	3.435	3.487	3.576	3.656	3.724	3.772
9.8	3.399	3.447	3.498	3.588	3.667	3.736	3.783
9.9	3.411	3.458	3.510	3.599	3.679	3.747	3.795
10.0	3.423	3.470	3.521	3.610	3.691	3.758	3.806
10.1	3.434	3.482	3.532	3.622	3.702	3.769	3.817
10.2	3.446	3.494	3.544	3.633	3.714	3.780	3.828
10.3	3.457	3.506	3.555	3.645	3.725	3.790	3.840
10.4	3.469	3.518	3.567	3.656	3.737	3.801	3.851
10.5	3.480	3.530	3.578	3.668	3.748	3.812	3.862
10.6	3.492	3.541	3.588	3.679	3.758	3.823	3.873
10.7	3.504	3.552	3.598	3.689	3.769	3.834	3.883
10.8	3.515	3.562	3.609	3.700	3.779	3.844	3.894
10.9	3.527	3.573	3.619	3.710	3.790	3.855	3.904
11.0	3.539	3.584	3.629	3.721	3.800	3.866	3.915
11.1	3.551	3.595	3.639	3.732	3.811	3.877	3.926
11.2	3.562	3.605	3.650	3.743	3.822	3.888	3.937
11.3	3.574	3.616	3.660	3.753	3.832	3.899	3.947
11.4	3.585	3.626	3.671	3.764	3.843	3.910	3.958
11.5	3.597	3.637	3.681	3.775	3.854	3.921	3.969
11.6	3.607	3.648	3.692	3.786	3.865	3.932	3.980
11.7	3.617	3.658	3.702	3.797	3.876	3.943	3.991
11.8	3.628	3.669	3.713	3.808	3.886	3.955	4.003
11.9	3.638	3.679	3.723	3.819	3.897	3.966	4.014
12.0	3.648	3.690	3.734	3.830	3.908	3.977	4.025

Pseudo Reduced Pressure P_r	Pseudo Reduced Temperature T_r 2.00	2.20	2.40	2.60	2.80	3.00
0.2	0	0	0	0	0	0
0.3	0.350	0.350	0.350	0.350	0.350	0.350
0.4	0.639	0.640	0.640	0.640	0.640	0.640
0.5	0.867	0.868	0.869	0.869	0.869	0.869
0.6	1.050	1.051	1.051	1.052	1.052	1.052
0.7	1.216	1.218	1.219	1.220	1.220	1.220
0.8	1.360	1.363	1.364	1.364	1.364	1.364
0.9	1.489	1.492	1.494	1.495	1.495	1.495
1.0	1.602	1.607	1.608	1.609	1.610	1.610
1.1	1.691	1.699	1.702	1.706	1.709	1.711
1.2	1.780	1.790	1.795	1.802	1.808	1.812
1.3	1.858	1.868	1.875	1.883	1.890	1.896
1.4	1.935	1.945	1.954	1.964	1.972	1.980
1.5	1.997	2.010	2.019	2.027	2.036	2.045
1.6	2.059	2.074	2.083	2.090	2.100	2.110
1.7	2.116	2.131	2.141	2.148	2.159	2.169
1.8	2.172	2.188	2.198	2.205	2.217	2.227
1.9	2.219	2.237	2.247	2.256	2.267	2.279
2.0	2.265	2.285	2.295	2.307	2.317	2.330
2.1	2.307	2.326	2.337	2.350	2.361	2.375
2.2	2.349	2.366	2.380	2.394	2.404	2.420
2.3	2.391	2.407	2.422	2.437	2.448	2.465
2.4	2.433	2.447	2.465	2.481	2.491	2.510
2.5	2.475	2.488	2.507	2.524	2.535	2.555
2.6	2.508	2.523	2.544	2.562	2.574	2.593
2.7	2.541	2.559	2.581	2.599	2.612	2.630
2.8	2.575	2.594	2.617	2.637	2.651	2.668
2.9	2.608	2.630	2.654	2.674	2.689	2.705
3.0	2.641	2.665	2.691	2.712	2.728	2.743
3.1	2.670	2.694	2.722	2.744	2.759	2.775
3.2	2.700	2.723	2.753	2.775	2.790	2.806
3.3	2.729	2.752	2.783	2.807	2.821	2.838
3.4	2.759	2.781	2.814	2.838	2.852	2.869
3.5	2.788	2.810	2.845	2.870	2.883	2.901
3.6	2.813	2.836	2.872	2.910	2.911	2.929
3.7	2.839	2.862	2.899	2.950	2.938	2.957
3.8	2.864	2.888	2.925	2.990	2.966	2.984
3.9	2.890	2.914	2.952	3.030	2.993	3.012
4.0	2.915	2.940	2.979	3.070	3.021	3.040
4.1	2.938	2.963	3.002	3.081	3.045	3.064
4.2	2.960	2.985	3.025	3.092	3.069	3.088
4.3	2.983	3.008	3.049	3.103	3.094	3.112
4.4	3.005	3.030	3.072	3.114	3.118	3.136
4.5	3.028	3.053	3.095	3.125	3.142	3.160
4.6	3.048	3.074	3.117	3.147	3.164	3.182
4.7	3.068	3.095	3.139	3.168	3.186	3.203
4.8	3.088	3.115	3.161	3.190	3.209	3.225
4.9	3.108	3.136	3.183	3.211	3.231	3.246
5.0	3.128	3.157	3.205	3.233	3.253	3.268
5.1	3.146	3.177	3.225	3.253	3.274	3.288
5.2	3.164	3.196	3.244	3.273	3.295	3.308
5.3	3.182	3.216	3.264	3.294	3.315	3.328
5.4	3.200	3.235	3.283	3.314	3.336	3.348
5.5	3.218	3.255	3.303	3.334	3.357	3.368
5.6	3.235	3.273	3.321	3.352	3.375	3.386
5.7	3.252	3.291	3.339	3.370	3.393	3.405
5.8	3.270	3.309	3.356	3.389	3.412	3.423
5.9	3.287	3.327	3.374	3.407	3.430	3.442
6.0	3.304	3.345	3.392	3.425	3.448	3.460
6.1	3.321	3.362	3.409	3.442	3.466	3.477
6.2	3.337	3.379	3.426	3.459	3.483	3.494
6.3	3.354	3.395	3.443	3.476	3.501	3.511
6.4	3.370	3.412	3.460	3.493	3.518	3.528
6.5	3.387	3.429	3.477	3.510	3.536	3.545
6.6	3.402	3.444	3.493	3.526	3.551	3.561
6.7	3.417	3.459	3.508	3.542	3.567	3.577
6.8	3.432	3.475	3.524	3.557	3.582	3.592
6.9	3.447	3.490	3.539	3.573	3.598	3.608
7.0	3.462	3.505	3.555	3.589	3.613	3.624
7.1	3.477	3.520	3.570	3.604	3.628	3.639
7.2	3.491	3.534	3.584	3.618	3.643	3.654
7.3	3.506	3.549	3.599	3.633	6.659	3.670
7.4	3.520	3.563	3.613	3.647	3.674	3.685
7.5	3.535	3.578	3.628	3.662	3.689	3.700
7.6	3.548	3.591	3.642	3.676	3.703	3.714
7.7	3.562	3.605	3.656	3.690	3.718	3.728
7.8	3.575	3.618	3.670	3.704	3.732	3.742
7.9	3.589	3.632	3.684	3.718	3.747	3.756
8.0	3.602	3.645	3.698	3.732	3.761	3.770
8.1	3.615	3.658	3.711	3.745	3.774	3.783
8.2	3.627	3.671	3.723	3.758	3.788	3.796
8.3	3.640	3.684	3.736	3.771	3.801	3.810
8.4	3.652	3.697	3.748	3.784	3.815	3.823
8.5	3.665	3.710	3.761	3.797	3.828	3.836
8.6	3.677	3.722	3.773	3.810	3.840	3.849
8.7	3.690	3.734	3.786	3.823	3.853	3.862
8.8	3.702	3.746	3.798	3.835	3.865	3.875
8.9	3.715	3.758	3.811	3.848	3.878	3.888
9.0	3.727	3.770	3.823	3.861	3.890	3.901
9.1	3.739	3.782	3.835	3.873	3.902	3.913
9.2	3.750	3.794	3.847	3.885	3.915	3.925
9.3	3.762	3.806	3.859	3.897	3.927	3.938
9.4	3.773	3.818	3.871	3.909	3.940	3.950
9.5	3.785	3.830	3.883	3.921	3.952	3.962
9.6	3.797	3.842	3.895	3.933	3.964	3.974
9.7	3.809	3.854	3.907	3.945	3.976	3.986
9.8	3.820	3.865	3.918	3.957	3.987	3.999
9.9	3.832	3.877	3.930	3.969	3.999	4.011
10.0	3.844	3.889	3.942	3.981	4.011	4.023
10.1	3.855	3.900	3.953	3.992	4.023	4.035
10.2	3.867	3.911	3.965	4.004	4.035	4.046
10.3	3.878	3.923	3.976	4.015	4.046	4.058
10.4	3.890	3.934	3.988	4.027	4.058	4.069
10.5	3.901	3.945	3.999	4.038	4.070	4.081
10.6	3.912	3.956	4.010	4.049	4.081	4.092
10.7	3.923	3.967	4.021	4.060	4.093	4.104
10.8	3.933	3.978	4.031	4.071	4.104	4.115
10.9	3.944	3.989	4.042	4.082	4.116	4.127
11.0	3.955	4.000	4.053	4.093	4.127	4.138
11.1	3.966	4.011	4.064	4.104	4.138	4.149
11.2	3.977	4.022	4.075	4.116	4.150	4.160
11.3	3.988	4.033	4.087	4.127	4.161	4.172
11.4	3.999	4.044	4.098	4.139	4.173	4.183
11.5	4.010	4.055	4.109	4.150	4.184	4.194
11.6	4.022	4.067	4.121	4.161	4.195	4.205
11.7	4.034	4.079	4.132	4.172	4.206	4.216
11.8	4.045	4.090	4.144	4.183	4.217	4.227
11.9	4.057	4.102	4.155	4.194	4.228	4.238
12.0	4.069	4.114	4.167	4.205	4.239	4.249

The absolute temperature T was removed from within the integral sign by assuming a constant average temperature in the flow string. This is not a serious assumption since temperature usually varies as a straight line function of depth.

The compressibility factors for natural gases are correlated as a function of pseudo reduced pressure and temperature.

$$P_r = \frac{P}{P_c} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

Table II — Flow String Weights and Sizes

Nominal Size In.	API Rating In.	Weight Per Ft	Outside Diameter In.	Inside Diameter In.
1¼	—	2.3 or 2.4	1.660	1.380
1½	—	2.9 or 2.748	1.900	1.610
2	2⅜	4.00	2.375	2.041
2	2⅜	4.5 or 4.7	2.375	1.995
2½	2⅜	5.887	2.875	2.469
2½	2⅞	6.25 or 6.5	2.875	2.441
3	3½	7.694	3.500	3.068
3	3½	8.50	3.500	3.018
3	3½	9.30	3.500	2.992
3	3½	10.2	3.500	2.922
3½	4	9.26 or 9.50	4.000	3.548
3½	4	11.00	4.000	3.476
4	4½	10.98	4.500	4.026
4	4½	11.75	4.500	3.990
4	4½	12.75	4.500	3.958
4½	4¾	16.00	4.750	4.082
4½	4¾	16.50	4.750	4.070
4¾	5	12.85	5.000	4.500
4¾	5	13.00	5.000	4.494
4¾	5	15.00	5.000	4.408
4¾	5	18.00	5.000	4.276
4¾	5	21.00	5.000	4.154
—	5¼	16.00	5.250	4.648
5	5½	17.00	5.500	4.892
5	5½	20.00	5.500	4.778
—	5¾	14.00	5.750	5.290
—	5¾	17.00	5.750	5.190
—	5¾	19.50	5.750	5.090
—	5¾	22.50	5.750	4.990
5⅝	6	20.00	6.000	5.350
6¼	6⅝	20.00	6.625	6.049
6¼	6⅝	24.00	6.625	5.921
6¼	6⅝	26.00	6.625	5.855
6¼	6⅝	28.00	6.625	5.791
6¼	6⅝	29.00	6.625	5.761
6⅝	7	20.00	7.000	6.456
6⅝	7	22.00	7.000	6.398
6⅝	7	24.00	7.000	6.336
6⅝	7	26.00	7.000	6.276
6⅝	7	28.00	7.000	6.214
6⅝	7	30.00	7.000	6.154
API	7⅝	34.00	7.625	6.765
7⅝	8	26.00	8.000	7.386
API	8¼	28.00	8.125	7.485
API	8¼	32.00	8.125	7.385
API	8¼	35.50	8.125	7.285
API	8¼	39.5 or 40.00	8.125	7.185
API	8¼	42.00	8.125	7.125
8¼	8⅝	24.00	8.625	8.097
8¼	8⅝	28.00	8.625	8.017
8¼	8⅝	32.00	8.625	7.921
8¼	8⅝	32.00	8.625	7.907
8¼	8⅝	36.00	8.625	7.825
8¼	8⅝	38.00	8.625	7.775
8¼	8⅝	43.00	8.625	7.651
8¼	8⅝	44.85	8.625	7.625
8⅝	9	34.00	9.000	8.290
8⅝	9	38.00	9.000	8.196
8⅝	9	40.00	9.000	8.152
8⅝	9	45.00	9.000	8.032
8⅝	9	54.00	9.000	7.812
API	9⅝	43.80	9.625	8.755
API	9⅝	47.20	9.625	8.681
API	9⅝	53.60	9.625	8.535
API	9⅝	57.40	9.625	8.451
9¼	9⅝	36.00	9.625	8.921
9⅝	10	33.00	10.000	9.384
9⅝	10	60.00	10.000	8.780
10	10¾	32.75	10.750	10.192
10	10¾	35.75	10.750	10.136
10	10¾	40.00	10.750	10.054
API	10¾	40.50	10.750	10.050
10	10¾	45.00	10.750	9.960
API	10¾	45.50	10.750	9.950
10	10¾	48.00	10.750	9.902
API	10¾	51.00	10.750	9.850
10	10¾	54.00	10.750	9.784

$$T_r = \frac{T}{T_c} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

P_r = Pseudo reduced pressure
T_r = Pseudo reduced temperature
P_c = Pseudo critical pressure
T_c = Pseudo critical temperature in degrees absolute

Differentiating Equation (7)

$$P_c dP_r = dP$$

and substituting Equations (7) and (9) in Equation (6); Equation (6) can be expressed in reduced form.

$$\frac{RT}{M}\int_{P_2}^{P_1}\frac{Z}{P}\,dP = \frac{RT}{M}\int_{P_{r_2}}^{P_{r_1}}\frac{Z}{P_r}\,dP_r \quad . \quad (10)$$

By arbitrarily setting a lower pressure limit of P_r of 0.2 the value of the integral can be evaluated:

$$\int_{P_2}^{P_1}\frac{Z}{P}\,dP = \int_{P_{r_2}}^{P_{r_1}}\frac{Z}{P_r}\,dP_r =$$

$$\int_{0.2}^{P_{r_1}}\frac{Z}{P_r}\,dP_r - \int_{0.2}^{P_{r_2}}\frac{Z}{P_r}\,dP_r \quad \ldots\ldots \quad (11)$$

Values of $\int_{0.2}^{P_r}\frac{Z}{P_r}\,dP_r$ have been determined in both graphical (Fig. 2) and tabular form (Table I) from the compressibility factor chart for natural gases as functions of reduced temperature and pressure.[3] A similar function was used by Fowler[4] in the direct solution for calculating the static bottom hole pressures of gas wells. Fowler's curves were calculated for methane.

The integrated average value of velocity v can also be expressed as a function of

$$\int_{P_{r_2}}^{P_{r_1}}\frac{Z}{P_r}\,dP_r$$

$$v = \frac{VW}{A} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (12)$$

where

W = Pounds gas flowing per second
A = Cross sectional area of flow path in sq ft

$$v = \left(\frac{RT}{M}\right)\left(\frac{Z}{P}\right)\left(\frac{W}{A}\right) \quad \ldots\ldots \quad (13)$$

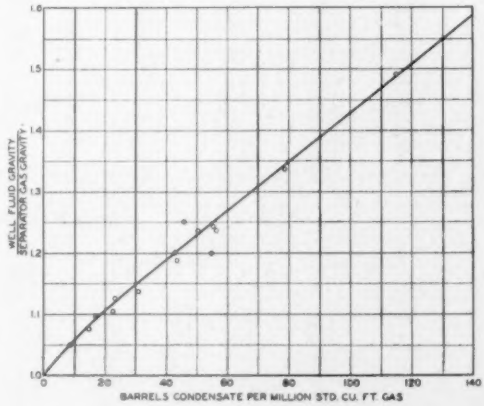

FIG. 3 — GRAVITY RATIO VS STOCK-TANK YIELD OF CONDENSATE.[3]

$$\bar{v} = \frac{\int_{P_2}^{P_1} v\,dP}{P_1 - P_2} = \frac{\left(\frac{W}{A}\right)\left(\frac{RT}{M}\right)\int_{P_{r2}}^{P_{r1}} \frac{Z}{P_r}\,dP_r}{\triangle P} \quad . \quad . \quad (14)$$

$$\bar{v}^2 = \left(\frac{W}{A}\right)^2\left(\frac{RT}{M}\right)^2 \frac{1}{(\triangle P)^2}\left[\int_{P_{r2}}^{P_{r1}} \frac{Z}{P_r}\,dP_r\right]^2 \quad (15)$$

$$\bar{v}^2 = \left(\frac{W}{A}\right)^2\left(\frac{RT}{M}\right)^2 \frac{1}{(\triangle P)^2}\left[\int_{0.2}^{P_{r1}} \frac{Z}{P_r}\,dP_r - \int_{0.2}^{P_{r2}} \frac{Z}{P_r}\,dP_r\right]^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

$$\text{Let } L_s = \frac{RT_{avg}}{M}\left[\int_{0.2}^{P_{r1}} \frac{Z}{P_r}\,dP_r - \int_{0.2}^{P_{r2}} \frac{Z}{P_r}\,dP_r\right]. \quad (17)$$

$$L_s = \frac{53.241\,T_{avg}}{G}\left[\int_{0.2}^{P_{r1}} \frac{Z}{P_r}\,dP_r - \int_{0.2}^{P_{r2}} \frac{Z}{P_r}\,dP_r\right]. \quad (18)$$

Where: G equals gas gravity (air = 1)

Then substituting Equations (10), (16) and (18) in Equation (4):

$$L = \frac{L_s}{1 + \frac{4f}{2\,g.D}\left(\frac{W}{A}\right)^2 \frac{(L_s)^2}{(\triangle P)^2}} \quad . \quad . \quad . \quad (19)$$

Further simplification results in:

$$L = \frac{L_s}{1 + 3.8085 \times 10^{-6} \frac{f\,Q^2\,G^2}{D^5} \frac{(L_s)^2}{(\triangle P)^2}} \quad . \quad . \quad . \quad (20)$$

Where:

L = depth in ft
Q = MMcf/D of gas at 14.65 and 60°F
D = diameter of tubing in ft
$\triangle P = P_1 - P_2 = P_c\ (\triangle P_r)$ in psia
G = gas gravity (air = 1)

Thus an expression relating the difference in elevation L between any two pressure limits P_2 and P_1 as a function of flow rate, gas gravity, tubing diameter, average flowing temperature, and correlating factor f is available.

Values of f can be obtained from Fig. 1, which is a plot of $f' = 4f$, as a function of Reynolds number and relative roughness. Values of $\int_{0.2}^{P_r} \frac{Z}{P_r}\,dP_r$ can be obtained from Fig. 2 or Table I, whichever is most convenient. The increments of pseudo reduced pressure and temperature of Table I are such that linear interpolation may be used. Table II lists the pertinent data on the various flow string sizes.

The literature contains many equations for the determination of the value of f. At present it appears that one of the best ways to determine f is by the relative roughness method.[5] To use the relative roughness method it is necessary to establish a value for the absolute roughness of the pipe wall. This can best be accomplished by an analysis of experimental flow data. Cullender and Binckley[3] have shown from data presented in U. S. Bureau of Mines Monograph 6,[8] that an absolute roughness of 0.0006 in. is satisfactory for clean pipe.

The factor f can be expressed as a power function of the Reynolds number and pipe diameter for a given absolute

Table III — Comparison of Observed Data and Calculated Results, Flow of Gas in Vertical Pipe

Part A — Dry Gas Wells

Test No.	Tubing Size In. Nominal	ID	Q MMcf/D	L Ft	T_{avg} °F	Specific Gravity of Flowing Fluid	Tubing Pressure P_w Psia	Sand Face Pressure P_s Observed Psia	Sand Face Pressure P_s Calculated Psia	Deviation Psia	Deviation Per Cent
1	2½	2.441	5.109	5190	92	0.600	1253.0	1495	1490	− 5	−0.334
2	2½	2.441	9.514	5190	94	0.600	1112.4	1478	1483	+ 5	+0.338
3	2½	2.441	14.068	5190	96	0.600	832.0	1475	1500	+25	+1.695
4	2½	2.441	6.299	4922	91	0.605	1297.4	1593	1554	−39	−2.448
5	2½	2.441	5.695	5195	92	0.595	1210.0	1462	1455	− 7	−0.479
6	2½	2.441	9.298	5195	93	0.595	1084.4	1452	1451	− 1	−0.069
7	2½	2.441	13.176	5195	94	0.595	802.4	1438	1412	−26	−1.808
8	2½	2.441	4.827	4750	93	0.602	1188.4	1411	1392	−19	−1.346
9	2½	2.441	8.025	4750	93	0.602	1099.4	1411	1389	−22	−1.559
10	2½	2.441	13.680	4750	95	0.602	764.4	1401	1382	−19	−1.356
11	2½	2.441	2.432	4764	90	0.599	1102.4	1260	1261	+ 1	+0.079
12	2½	2.441	4.127	4764	90	0.599	1043.4	1216	1236	+20	+1.618
13	2½	2.441	6.167	4764	90	0.599	923.4	1156	1148	− 8	−0.692
14	2½	2.441	3.810	5242	93	0.591	1433.4	1690	1654	−36	−2.130
15	2½	2.441	5.379	5242	93	0.591	1302.4	1579	1550	−29	−1.837
16	2½	2.441	7.663	5195	92	0.595	919.4	1257	1220	−37	−2.943
17	2½	2.441	10.598	5195	92	0.595	680.4	1247	1173	−76	−6.308
18	2½	2.441	11.841	5195	92	0.595	650.4	1247	1227	−20	−1.604
19	2½	2.441	4.384	5195	92	0.595	1028.4	1240	1223	−17	−1.371
20	2½	2.441	6.585	5195	92	0.595	966.4	1230	1226	− 4	−0.325

Part B — Distillate Wells

Test No.	Tubing Size In. Nominal	ID	Q MMcf/D	L Ft	T_{avg} °F	Gas/Oil Ratio MCF/Bbl	°API Gravity Liquid	Specific Gravity of Flowing Fluid	P_w Psia	P_s Observed Psia	P_s Calculated Psia	Deviation Psia	Deviation Per Cent
21	2.0	1.995	4.461	5529	122.5	341.2	47.7	0.7083	1873	2266	2307	+41	+1.809
22	2.0	1.995	3.765	5529	122.5	341.2	47.7	0.7083	1951(?)	2276	2370	+94	+4.130
23	2.0	1.995	3.055	5529	121.0	341.2	47.7	0.7083	1953	2287	2348	+61	+2.667
24	2.0	1.995	2.675	9110	157.5	40.7	54.0	0.7163	1979	2688	2593	−95	−3.534
25	2½	2.441	4.803	8226	164.0	65.8	51.3	0.761	2272	2893	2944	+51	+1.763
26	2½	2.441	3.207	8226	161.0	65.8	51.3	0.761	2320	2902	2970	+68	+2.343
27	2½	2.441	1.338	8226	160.0	65.8	51.3	0.761	2373	2911	3003	+92	+3.160
28	2.0	1.995	5.153	5790	121.5	787.89	35.3	0.604	2122	2565	2556	− 9	−0.351
29	2.0	1.995	3.522	5790	119.0	787.89	35.3	0.604	2202	2593	2580	−13	−0.501
30	2.0	1.995	2.760	5790	118.5	787.89	35.3	0.604	2232	2601	2593	− 8	−0.308
31	2.0	1.995	2.046	5790	117.5	787.89	35.3	0.604	2260	2605	2610	+ 5	+0.192

roughness.[5] For an absolute roughness of 0.0006 in. and in terms of Q, G, D and viscosity μ:

$$f = \frac{7.7302 \times 10^{-2}\ Q^{0.955}\ D^{-0.955}\ G^{-0.045}}{\mu^{0.955}} \quad \ldots\ldots (21)$$

Substituting Equation (21) into Equation (20), gives:

$$L = \frac{L_s}{1 + 2.94409 \times 10^{-5}\ \frac{Q^{1.955}\ G^{1.955}\ L_s^{\,2}}{D^{5.955}\ \mu^{0.955}\ (\triangle P)^2}} \quad \ldots (22)$$

where μ = viscosity in pounds per foot second.

Comparison with Field Data

In order to present an idea of the deviation of the calculated results from field measurements for a given set of conditions, Table III was prepared. Comparisons were made on 20 flowing conditions in dry gas wells from a given field and 11 flowing conditions in distillate wells from different fields. Equation (22) was used to calculate the pressure traverses. Only sandface pressures were compared. The deviations shown reflect to a considerable degree the accuracy of the data used in making the calculations and the accuracy of the recorded flowing pressures, not the accuracy of the mathematical development. In the cases of the dry gas wells, for example, most of the deviations are negative, indicating that perhaps for the tubing in this field, the absolute roughness and thus the factor f were slightly underestimated. However, the agreement between the calculated and observed results is good.

The application of Equation (20) or (22) to distillate wells may be somewhat limited by the amount of liquid in the flow string. However, it is of interest to note that for a ratio as low as 40,000 cu ft per bbl, reasonable agreement is still obtained. The higher the gas/oil ratio the more accurate one can expect the calculated results to be. It is likely that the procedures can be applied to wells with ratios considerably lower than 40,000 cu ft per bbl without appreciable error in the computed results. Table III also summarizes the data used to calculate the pressure traverses.

The gas gravity G of Equation (20) or (22) can be calculated from the composition of the flow stream or experimentally measured. In the case of distillate wells, if the composition is not available, gas gravity may be calculated from the following equation:[6]

$$G = \frac{G_g + \frac{4{,}591\ G_o}{R_s}}{1 + \frac{1{,}123}{R_s}} \quad \ldots\ldots\ldots\ldots (23)$$

where:

G_g = Separator gas gravity
G_o = Specific gravity of condensate
R_s = gas/liquid ratio, cu ft/bbl

Rzasa and Katz[5] developed a simple correlation based on field data, Fig. 3, from which can be estimated the well fluid gravity of distillate wells, if Equation (23) is not used.

The pseudo (molal average) critical temperature and pressure of the gas may be calculated from the gas composition. If composition is not available, Fig. 4 may be used to estimate the pseudo critical temperature and pressure.[2]

The viscosity of the natural gas may be obtained from Figs. 5 and 6.[7]

In the case of flow through the annulus, D^5 of Equation (20) must be replaced by[3]

$$D^5 = (D_1 + D_2)^3\ (D_1 - D_2)^2 \quad \ldots\ldots\ldots (24)$$

and $D^{5.955}$ of Equation (22) by[3]

$$D^{5.955} = (D_1 + D_2)^{1.955}\ (D_1 - D_2)^{2.955} \quad \ldots\ldots (25)$$

Where D_1 = Internal diameter of casing in ft
D_2 = External diameter of tubing in ft

The use of Equation (22) is perhaps best explained by a numerical example.

Example: Calculate the sandface pressure of gas-distillate well from the following surface measurements:

Q = 5.153 MMcf/D
D = 1.995 in. = 0.1663 ft
Gravity separator gas = 0.600
Gravity distillate = 35.3 °API
Separator gas/liquid ratio = 787.89 Mcf/bbl
Depth of well = 5,790 ft
Bottom hole temperature = 160°F
Well head flow temperature = 83°F
Tubing pressure = 2,122 psia
Viscosity = 0.0185 centipoise (Figs. 5 and 6)
= 1.2432×10^{-5} lb/ft-sec

$$\text{Average flow string temperature} = \frac{160 + 83}{2} = 121.5°\text{F}$$
$$= 581.5°\text{R}$$

Gas gravity of flow stream from Equation (23)

$$G = \frac{G_g + \frac{4{,}591\ G_o}{R_s}}{1 + \frac{1{,}123}{R_s}}$$

$$G = \frac{0.600 + \frac{(4{,}591)\ (0.8483)}{787{,}890}}{1 + \frac{1{,}123}{787{,}890}}$$

$$G = 0.604$$

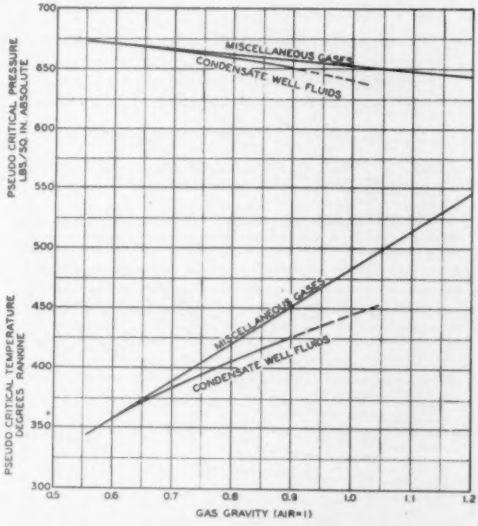

FIG. 4 — PSEUDO CRITICAL PROPERTIES OF CONDENSATE WELL FLUIDS AND MISCELLANEOUS NATURAL GASES.[2]

Pseudo critical temperature and pressure from Fig. 4

$P_c = 671$ psia

$T_c = 360°R$

Pseudo reduced temperature

$$T_r = \frac{T}{T_c} = \frac{581.5}{360.0} = 1.615$$

Calculate L_s for various downhole pressures

1	2	3	4	5
P	P_r	$\int_{0.2}^{P_r} \frac{Z}{P_r}\,dP_r$	$\int_{.2}^{P_{r_1}} \frac{Z}{P_r}\,dP_r - \int_{.2}^{P_{r_2}} \frac{Z}{P_r}\,dP_r$	L_s (Equation 18)
2122	3.162	2.564	———	———
2300	3.428	2.632	0.068	3483.7
2600	3.875	2.734	0.170	8709.7

Column 1 shows the various downhole pressures for which L_s is to be calculated. Column 2 is the pseudo reduced pressure and is column 1 divided by 671 psia. Column 3 was obtained from Table I by interpolation. Column 4 is the value of $\int_{P_{r_2}}^{P_{r_1}} \frac{Z}{P_r}\,dP_r$ between the downhole pressure and the tubing pressure. Column 5, L_s is calculated from Equation (18).

The various depths L corresponding to the pressures P of column 1 are then calculated from Equation (22).

P	L
2,122	0
2,300	2,445
2,600	6,365

Fig. 7 shows a plot of this pressure traverse. At a depth of 5,790 ft the sandface pressure is 2,556 psia as obtained by plotting the traverse on large scale graph paper.

CALCULATION OF STATIC BOTTOM-HOLE PRESSURES OF GAS WELLS

Fowler[4] suggested the use of factors similar to those listed in Table I or plotted on Fig. 2 in a method involving the direct solution of the static bottom hole pressures of gas wells.

For zero flow rate ($Q = 0$) Equations (20) and (22) reduce to:

$$L = L_s = \frac{53.241\ T_{avg}}{G}\left[\int_{0.2}^{P_{r_1}} \frac{Z}{P_r}\,dP_r - \int_{0.2}^{P_{r_2}} \frac{Z}{P_r}\,dP_r\right] \quad \ldots\ldots\ldots\ (26)$$

By rearranging.

$$\int_{.2}^{P_{r_1}} \frac{Z}{P_r}\,dP_r = \frac{LG}{53.241\ T_{avg}} + \int_{0.2}^{P_{r_2}} \frac{Z}{P_r}\,dP_r \quad . \quad (27)$$

Equation (27) is a direct solution for the static bottom hole pressure.

The factor corresponding to tubing pressure $\int_{0.2}^{P_{r_2}} \frac{Z}{P_r}\,dP_r$ can be obtained directly from Table I or Fig. 2, $\frac{LG}{53.241\ T_{avg}}$ can be evaluated directly, the sum of the two then gives the factor $\int_{0.2}^{P_{r_1}} \frac{Z}{P_r}\,dP_r$ corresponding to the bottom hole pressure. The pseudo reduced bottom hole pressure can be ob-

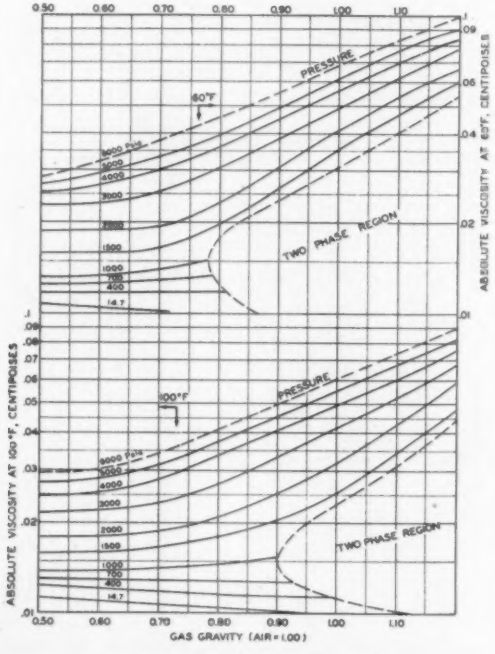

FIG. 5 — VISCOSITY OF NATURAL GAS.[1]

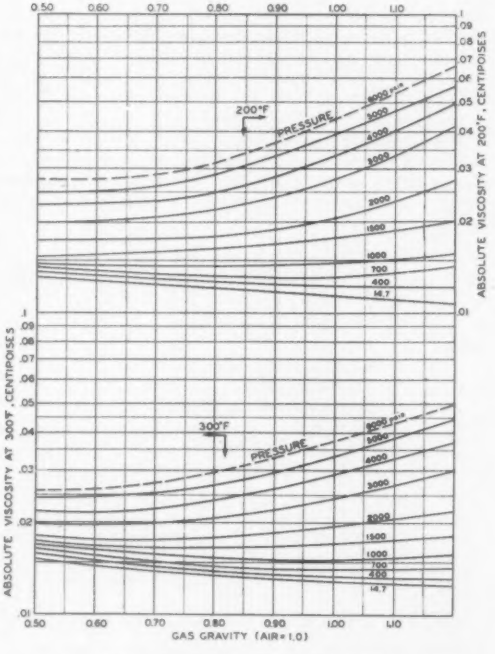

FIG. 6 — VISCOSITY OF NATURAL GAS.[1]

tained from Table I or Fig. 2. Multiplying this pseudo reduced pressure by the pseudo critical pressure gives the static bottom hole pressure.

Example: Calculate the static bottom hole pressure of a gas well having a depth of 5,790 ft. The gas gravity is 0.600 and the pressure at the well head is 2,300 psia. The average temperature of the flow string is 117°F.

From Fig. 4

$$T_c = 358°R$$
$$P_c = 672 \text{ psia}$$
$$T_r = \frac{T}{T_c} = \frac{117 + 460}{358} = 1.612$$
$$P_{r_2} = \frac{2300}{672} = 3.423$$

From Table I

$$\int_{0.2}^{P_{r_2}} \frac{Z}{P_r}\, dP_r = 2.629$$
$$\frac{LG}{53.241\ T_{avg}} = \frac{(5{,}790)\ (.600)}{(53.241)\ (577)} = 0.113$$

Therefore from Equation (27):

$$\int_{0.2}^{P_{r_1}} \frac{Z}{P_r}\, dP_r = 2.629 + 0.113 = 2.742$$

From Table I 2.742 at a T_r of 1.612 corresponds to a P_r of 3.918

$$P = (3.918)\ (672) = 2{,}633 \text{ psia}$$

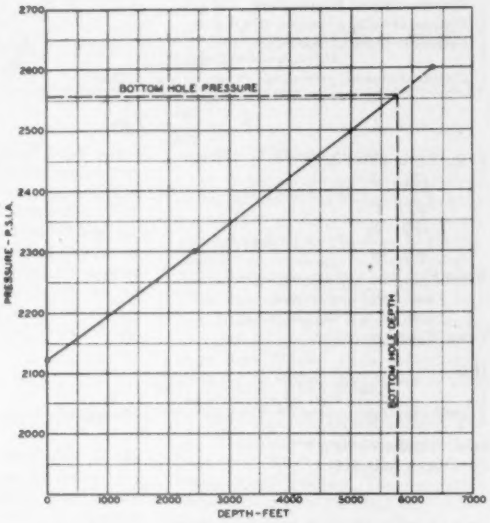

FIG. 7 — PRESSURE TRAVERSE OF FLOWING GAS WELL.

HORIZONTAL FLOW OF GAS

Equations for use in estimating the capacity of pipe lines quite often disregard the deviation of the natural gas from ideal gas behavior. For low pressures this error is not serious. For high pressures, this deviation from ideality must be taken into consideration. An equation can be derived which makes use of the factors tabulated in Table I or of Fig. 2.

Starting with the general flow equation and assuming no difference in elevation ($\triangle h = 0$), no external work ($W_s = 0$) and a negligible kinetic energy term, then:

$$\int_{P_2}^{P_1} V\,dP + W_f = 0 \qquad (28)$$

It has been shown in the foregoing sections that:

$$\int_{P_2}^{P_1} V\,dP = \frac{53.241\ T_{avg}}{G}\left[\int_{0.2}^{P_{r_1}} \frac{Z}{P_r}\, dP_r - \int_{0.2}^{P_{r_2}} \frac{Z}{P_r}\, dP_r\right] \qquad (29)$$

and

$$W_f = \frac{4fL}{2\ g_c D}\left(\frac{53.241\ T_{avg}}{G}\right)^2 \left[\int_{0.2}^{P_{r_1}} \frac{Z}{P_r}\, dP_r - \int_{0.2}^{P_{r_2}} \frac{Z}{P_r}\, dP_r\right]^2 \left(\frac{W}{A}\right)^2 \frac{1}{(\triangle P)^2} \qquad (30)$$

by substitution of Equations (29) and (30) into Equation (28) and division by Equation (29)

$$1 - \frac{4fL}{2\ g_c D}\left(\frac{53.241\ T_{avg}}{G}\right)\left[\int_{0.2}^{P_{r_1}} \frac{Z}{P_r}\, dP_r - \int_{0.2}^{P_{r_2}} \frac{Z}{P_r}\, dP_r\right]\frac{1}{(\triangle P)^2}\left(\frac{W}{A}\right)^2 = 0 \qquad (31)$$

Simplification of Equation (31) then results in:

$$Q = \left[\frac{4{,}976.18}{fL\ T_{avg}\ G}\cdot\frac{D^5\ (\triangle P)^2}{\left[\int_{0.2}^{P_{r_1}} \frac{Z}{P_r}\, dP_r - \int_{0.2}^{P_{r_2}} \frac{Z}{P_r}\, dP_r\right]}\right]^{0.5} \qquad (32)$$

where

Q = MMcf/D of gas at 14.65 and 60°F
D = Diameter of tubing in ft
$\triangle P = P_1 - P_2$ in psia
G = Gas gravity (air = 1)
T_{avg} = Average flowing temperature
L = Length of line in ft

Expression of the f factor in terms of Q, G, D, and μ, Equation (21), and substitution into Equation (32), results in:

$$Q = \left[\frac{6.43732 \times 10^2\ D^{2.666}\ (\triangle P)^2}{L\ T_{avg}\ G^{0.916}\ \mu^{0.032}\left[\int_{0.2}^{P_{r_1}} \frac{Z}{P_r}\, dP_r - \int_{0.2}^{P_{r_2}} \frac{Z}{P_r}\, dP_r\right]}\right]^{0.5165} \qquad (33)$$

where μ = viscosity in lb/ft-sec

Example: Calculate the capacity of a pipe line consisting of 50 miles of 26 in. OD pipe having an ID of 25.44 in. The natural gas has a specific gravity of 0.6124. The temperature of the flowing gas is 60°F. The upstream pressure is 825 psia and the downstream pressure 565 psia.

The analysis of the gas is:

Component	Mole Per Cent
CO_2	0.90
N_2	1.38
CH_4	91.75
C_2H_6	4.31
C_3H_8	1.08
iC_4H_{10}	0.17
nC_4H_{10}	0.21
iC_5H_{12}	0.02
nC_5H_{12}	0.02
C_6H_{14}	0.11
C_7H_{16} plus	0.05
	100.00

Pseudo critical temperature, 358.4°R
Pseudo critical pressure, 674.0 psia
Pseudo reduced temperature, 1.45

Pseudo reduced pressures, $P_{r_1} = \frac{825}{674} = 1.224$

$$P_{r_2} = \frac{565}{674} = 0.838$$

From Table I or Fig. 2

$$\int_{0.2}^{P_{r_1}} \frac{Z}{P_r}\, dP_r = 1.706 \text{ at } P_{r_1}$$

$$\int_{0.2}^{P_{r_2}} \frac{Z}{P_r}\, dP_r = 1.373 \text{ at } P_{r_2}$$

From Fig. 5 at average pressure
$\mu = 0.0135$ centipoise
$\mu = 9.072 \times 10^{-6}$ lb/ft sec
From Equation (33),

$$Q = \left[\frac{(6.43732 \times 10^6)\ (2.12)^{5.000}\ (260)^2}{(5280)\ (50)\ (520)\ (0.6124^{-0.000}(9.072 \times 10^{-6})^{+0.000}(1.706-1.373)}\right]^{0.5000}$$

$$Q = (14.32489 \times 10^4)^{0.5000}$$
$$Q = 462.0 \text{ MMcf/D}$$

CALCULATION OF ISOTHERMAL HORSEPOWER REQUIRED TO COMPRESS A NATURAL GAS

Quite often it is necessary to calculate the isothermal horsepower required to compress a natural gas taking into consideration the deviation from ideal gas behavior. Starting with the general flow equation, for any compression operation, there is no difference in elevation ($\triangle h = 0$), there is a negligible kinetic energy term $\left(\frac{\triangle v^2}{2g_c} = 0\right)$ and no energy loss, ($W_f = 0$), then:

$$\int_{P_1}^{P_2} V dP + W_s = 0$$

$$W_s = \int_{P_2}^{P_1} V dP$$

Since by definition, W_s is work done by the fluid while in flow, work done on the fluid by an external source would then be numerically negative.

From Equation (29)

$$W_s = \int_{P_2}^{P_1} V dP = \frac{53.241\ T}{G}\left[\int_{0.2}^{P_{r_1}} \frac{Z}{P_r}\, dP_r - \int_{0.2}^{P_{r_2}} \frac{Z}{P_r}\, dP_r\right]$$

Expressing the work W_s in terms of theoretical isothermal horsepower required to compress 1,000,000 standard cu ft of gas per day (60°F, 14.65 psia), results in:

$$HP = 0.08531\ T\left[\int_{0.2}^{P_{r_1}} \frac{Z}{P_r}\, dP_r - \int_{0.2}^{P_{r_2}} \frac{Z}{P_r}\, dP_r\right]. \quad . \quad (34)$$

Example: Calculate the theoretical isothermal horsepower necessary to compress 1,000,000 standard cu ft per day of a natural gas of 0.600 gravity (air = 1) from 200 to 1,000 psia at 100°F.

From Fig. 4
$T_c = 358$°R
$P_c = 671$ psia

$$T_r = \frac{100 + 460}{358} = 1.564$$

$$P_{r_1} = \frac{200}{671} = 0.298$$

$$P_{r_2} = \frac{1000}{671} = 1.490$$

From Table I or Fig. 2

$$\int_{0.2}^{0.298} \frac{Z}{P_r}\, dP_r = 0.343$$

$$\int_{0.2}^{1.490} \frac{Z}{P_r}\, dP_r = 1.920$$

From Equation (34)

$$HP = 0.08531\ T\left[\int_{0.2}^{P_{r_1}} \frac{Z}{P_r}\, dP_r - \int_{0.2}^{P_{r_2}} \frac{Z}{P_r}\, dP_r\right]$$

$HP = 0.08531\ (560)\ (0.343-1.920)$
$HP = -75.34$ hp per 1,000,000 standard cu ft of gas per day.

In other words, the theoretical isothermal horsepower necessary to compress 1,000,000 standard cu ft of gas per day is 75.34 hp.

CONCLUSION

Equations have been derived for the calculation of the sandface pressure of flowing gas wells, the static bottom hole pressure of gas wells, and the capacity of gas transmission lines, which take into consideration the variation of the compressibility factor of the gas with pressure. This variation with pressure has been put into both graphical and tabular form. These factors can also be used to calculate rigorously the theoretical isothermal horsepower necessary to compress a natural gas. Examples demonstrating the use of the various equations are given. In the case of the sandface pressure of flowing gas wells, comparison of the calculated results with field measured results are made for 31 different flowing conditions, for 11 dry gas and distillate wells. The agreement between observed and calculated results is good.

ACKNOWLEDGMENT

The author wishes to acknowledge his indebtedness to M. H. Cullender and C. W. Binckley of the Natural Gas Department of the Phillips Petroleum Co. for the aid extended him during the development of this paper, to the Railroad Commission of Texas for providing the data on the distillate wells and to the management of the Phillips Petroleum Co. for permission to publish this report.

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The Drift of Things

. . . as followed by **EDWARD H. ROBIE**
Secretary AIME

Changes in Washington

Not often do we refer in these columns to what is going on in Washington. Several other organizations cover affairs in the national capital satisfactorily and we confess that their reports make pretty tough reading for us. The lighter stories about Washington appeal to us more, such as the one in the September issue of *Pay Dirt*, about the small mine operator who put in a hectic week going from one office to another trying to get things done. The most unusual thing that happened, he said, was when he took out a blonde the last evening he was there. Following dinner he asked for special favors, and she slapped him in the face. "You know," he said, "that was the first definite answer I had had all that week."

But we do feel that Jim Boyd's exit from the Washington scene is worthy of note. Dr. Boyd was appointed director of the Bureau of Mines four years ago, succeeding Dr. R. R. Sayers. John L. Lewis took violent exception to his appointment and for some time one of Colorado's senators blocked his confirmation. As a result he served without compensation for two years. Not long ago he was made head of the Defense Minerals Administration, though still keeping his title as director of the Bureau. He is reported to have differed with Interior Secretary Oscar L. Chapman on several matters, including payment of subsidies to mineral producers and the synthetic fuels program. He was therefore relieved of his duties and Dr. W. C. Schroeder became acting administrator. Also many of the DMA powers were transferred to a still newer organization, the Defense Materials Procurement Agency, headed by Jess Larson. Larson has asked Howard I. Young to become his deputy in charge of the Agency's metals and minerals section, with Simon D. Strauss and Alan Bateman as advisors. Then, on the first of October, President Truman announced the resignation of Dr. Boyd as director of the Bureau of Mines. He has found what should be a much happier home with the Kennecott Copper Corp., which he joined Oct. 16 in an executive capacity.

Probably some political sagacity and a willingness to follow administration policies are required of a bureau chief in Washington, making the climate inauspicious for an independent and objective thinker and doer. However, we can at least hope that when a new head for the Bureau of Mines is chosen, he will be a man of professional stature rather than primarily a political appointee.

The Chemical Society's 75th

As this is written, New York is the scene of the American Chemical Society's Diamond Jubilee celebration. Four years ago — one year late, for the AIME was founded in 1871—the AIME had a similar celebration. Our official representative at the Chemical Society's 75th birthday, Carleton C. Long, presented for us an engrossed scroll of greeting which read: "The American Institute of Mining and Metallurgical Engineers extends its most cordial congratulations to the American Chemical Society upon having so successfully attained the seventy-fifth anniversary of its founding. The Institute is proud that its roll contains the names of many members of the Society who have attained world-wide distinction in our related fields, and who have added substantially to our national industrial progress. May the Society in the future raise still further the high scientific and technical level of the chemical industry for which it is so largely responsible."

The Society now has more than 66,000 members, of whom 16,000 are chemical engineers. It is the largest scientific society in the world. It embraces 20 professional divisions, indicating the wide scope of the chemical industry. Really, almost every manufacturing industry in the country depends to a considerable extent on chemistry, as do many of the professions as well, conspicuously that of medicine. At the New York meeting 720 technical papers were presented at 129 sessions, covering 80 general subjects of scientific interest.

Bureau of Mines Films

An important activity of the Bureau of Mines that perhaps has not had the recognition it deserves is its motion picture work. Not only does the Bureau promote the making of films covering the mining, metallurgic, petroleum, and allied industries, but it maintains a free loan library of more than 16,000 reels. Last year its motion pictures were shown more than 177,000 times before audiences of 12 million people, not including showings by television.

This is one Government activity, and one of the more worthwhile ones it may be added, which costs the taxpayers comparatively nothing. The companies whose operations are depicted in the films have been eager to cooperate and to pay all production costs, even though the Bureau does not allow any trade marks, trade names, or advertising material to be shown. The only company identification is the name of the sponsoring company at the beginning and end of each film. Apparently the companies feel that even this modest mention of their name is worth the cost of the film in making for better employe morale and good public relations. Then, too, they have a sense of professional responsibility and pride in showing an interested public the highlights of their practice. They choose their own producing company, but the Bureau scrutinizes the scenario to make sure that the picture will be suitable for public showing on a non-commercial basis. Many, if not most, of the most recent films are in color. Both silent and sound films are included in the library.

Any companies that feel their operations are likely to be of sufficient public interest to warrant film recording should apply to M. F. Leopold, Bureau of Mines, Washington 25, D. C. Leopold, who joined the Bureau when it was created in 1910 and recently received the Interior Department's gold medal for distinguished service, is well known throughout the mineral industry. Those groups who wish to borrow the films for showing should apply to the Bureau of Mines Graphic Services Section, 4800 Forbes St., Pittsburgh 13. A catalog is available, as well as special publicity releases on all the new films as issued.

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Management

Continued from Page 21, Section 1

for those engineers who develop abilities and interests beyond the solution of technical problems.

He then launched into a discussion of the job of management as contrasted to the philosophy as discussed above. The manager's job, he said, is first to decide upon a plan and second, to build an organization to carry it out. He then went on to illustrate the engineer's place in such a scheme.

When the engineer becomes a manager, he must, of necessity, seek out and consider all facets of a certain problem, many of which are outside those of a strict engineering nature, such as the effect of legislation, taxes, marketing and personnel problems on the projects which were dealt with on only an engineering basis heretofore. His problem as a manager is seldom clear cut and is often contradictory, much more so than with a straight engineering function even though such functions may also be based on certain assumptions. While, Bowlby stated, it would be contrary to the principles of business organization for an engineer, in his zeal to become a good manager, to assume the functions of, say, the lawyers, the accountants and the tax men by adding to an engineering proposal a discussion of the problems of these other experts; still, engineers who aspire to managerial positions, should be inquisitive about what happens to proposals after they leave the engineering department and to seek out the opinions of those in other departments who will be consulted before a project is approved.

That part of a manager's job which involves a decision based upon a plan, discussed above, is still pretty close to engineering. However, the building and leading of an organization capable of carrying out the decision is by far the more important and more difficult part of the task because this reaches the heart of management — getting the job done through someone else — the part engineers know the least about.

The most important ingredient in management, Bowlby said, is the approach to human relations. Imagination, enthusiasm, loyalty, aggressiveness, and all of the other desirable attributes in an organization are individual traits and can only be developed by careful planning and nurturing on the part of the manager. Although the handling of such an abstract quantity as human relationships may be hard for a technically trained mind to master, Bowlby stressed that an emphasis on human qualities and their understanding is, in the end, a requisite of the first order in good management.

Fortunately, the colleges are realizing the importance of human relationships and are now requiring engineers to take courses in Humanities — courses designed to teach people to get along with one another and function as a group. Moreover, most oil companies have adopted training programs for new technical people just out of school, and, while these programs may vary among the different companies, they all perform the same worthwhile function; namely to give the trainee an introduction to all of the facilities at his disposal and also to provide a means whereby he may understand the people with whom he will work and learn to work with them harmoniously.

Having disposed of authority and responsibility, and having briefly tried to show the importance of human relations, Bowlby moved to the third magic word of management — accountability — which involves chiefly the ability to

Continued on Page 5, Section 2

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Personals

R. G. Sohlberg is now manager of the United Geophysical Co. of Canada, with offices in Calgary. He was formerly with the Standard Oil Co. of California.

+

William Gruenerwald has announced the opening of his offices as consulting geologist in the Pure Oil Building, Chicago, Ill. A graduate of Northwestern University, Gruenerwald acquired his professional experience as mining and petroleum geologist in many parts of the world including the Philippines, China, Tibet, Central and West Africa, Canada, Brazil, Argentina and Venezuela. In the United States, he has worked for major oil companies in the Gulf Coast region, West Texas and the Rocky Mountain states. For the past two years he has been associated with the Paul Weir Co., coal consultants of Chicago.

+

Sealey

Butterworth

F. C. Sealey and E. M. Butterworth have been elected vice-presidents of California Texas Oil Co., Ltd. Sealey has been associated with the oil industry since he joined The Texas Co. in 1917 as an assistant geologist. The past 13 years have been devoted to petroleum producing activities abroad, and since July, 1949, he has been in charge of producing and exploration for the Caltex-Bahrein group of companies, with headquarters in New York.

Butterworth, who is a geologist by training, began his oil business career after graduation from the University of California in 1916. He was for a considerable period active in the East Indies, beginning in 1924, when he conducted a group of exploration men in that area. He has been directly concerned with government relations in Sumatra and New Guinea for the past several years for the Caltex-Bahrein group.

Phillip Maverick, formerly petroleum geologist for the Tulsa, Okla., office of the Securities and Exchange Commission, has moved to Midland, Tex., where he will resume his work in geological exploration.

+

Jesse Shelton Dickerson is now on extended active duty with the U. S. Air Force.

+

John F. Eckel is with the Carter Oil Co., Tulsa.

+

Robert Gaymard has joined the Schlumberger Well Surveying Corp., Houston. He has been a petroleum engineer with the S. N. Repal, Algeria.

+

John Austin Jones is with Superior Oil Co., Crossville, Ill.

+

Carl C. Lavery is safety engineer, Houston Contracting Co., Houston.

+

Le Moyne W. Myers, Socony-Vacuum Oil Co., has been transferred from Caracas, Venezuela, to New York.

+

Ralph E. McAvoy has been promoted to assistant district superintendent, Sinclair Oil and Gas Co., Tulsa.

+

Rudolph L. Marker is presently working as a petroleum engineer trainee for the Continental Oil Co., Big Spring, Tex.

+

William J. McPherson has resigned from Imperial Oil, Ltd., Calgary, Alberta, to accept a position with the Calvan Consolidated Oil and Gas Co., Ltd., Calgary, Alberta.

+

Donald D. Utterback has joined the Freeport Sulphur Co., oil division, New Orleans. He has been with the Houston Oil Co., Houston.

+

Newton J. Winn has joined the Gulf Oil Corp., Wichita Falls, Tex.

+

Arthur A. McArthur has joined the staff of The Texas Co., Houston, as district reservoir engineer.

Robert H. McLemore of Welex Jet Services, Inc., Fort Worth, was elected to the post of executive vice-president and general manager of the company at the regular quarterly directors' meeting held October 17. He was formerly vice-president of operations. Before joining Welex in 1945 McLemore was district engineer for the Sun Oil Co. in Dallas.

+

J. L. Minahan, consulting geological engineer, is now doing geological, valuation and related work with temporary headquarters in Casper, Wyo. He was formerly with the U. S. Geological Survey in Thermopolis, Wyo.

+

John T. Gary was recently named division petroleum engineer of the Kansas Division of Continental Oil Co., with offices in Wichita. He was formerly in the company's Houston office.

+

William M. Capps, engineer with the Amerada Petroleum Corp., has been transferred from Seminole, Tex., to Tulsa, Okla.

+

P. D. Grommon, Jr., is now assistant district superintendent, The Texas Co., Pampa, Tex.

+

William W. Goode, Jr., has been made division manager of the Louisiana Coast division, Schlumberger Well Surveying Corp., Lafayette, La.

+

Robert W. Harrison has organized his own consulting firm, Robert W. Harrison and Co., at Houston, Tex., specializing in petroleum engineering and geology. He was previously associated with the R. B. Mitchell Co., in Houston.

+

W. R. Jay is now with the Halliburton Oil Well Cementing Co., Dhahran, Saudi Arabia.

Management

Continued from Page 3, Section 2

communicate or ability of self-expression. Considerable criticism has been levied on engineers as a group by industry and the engineering profession itself because of the group's shortcomings insofar as its ability to express its ideas well in writing and in speaking. As a result, colleges and universities have provided time for compulsory courses in English which should aid in the solution of this problem. Bowlby stressed that the success of a young engineer depends upon his capacity to write clearly and not on his ability to apply the principles of mathematics or the natural sciences.

Imagination on the part of an engineer is also lacking, Bowlby felt. He stressed that there cannot be too little imagination used in the oil business and encouraged the engineer to be less of a doubter and conservatist when faced with an idea or plan that is contrary to his established ways. He felt that any lack of imagination probably comes from intellectual laziness, because it isn't inherent to a technical training. He further stressed that the principal flow of ideas, both technical and organizational, should be from the staff of management rather than vice versa. Engineers, particularly, should suggest the unusual and the unconventional and let management supply the conservatism. It is necessary for an engineer to develop a strong imaginative approach to his problems if he aspires to undertake the increasing responsibility of management, should the opportunity arise.

Bowlby concluded by briefly mentioning that, although most engineers may aspire to top managerial positions, it is not necessary that they do so because the great shortage of engineering talent in this country indicates that the good technical man without managerial inclination may be paid just as well and find as much satisfaction in his work as he would in the highest managerial position. He felt that it was obvious to him that the first requisite and first ambition of an engineer should be to strive for expert technical proficiency and that, having accomplished this, a managerial capacity would logically follow if the engineer desires it. ★ ★ ★

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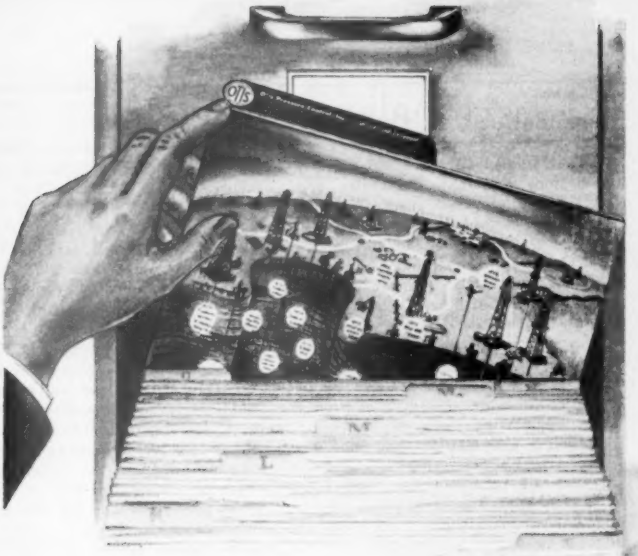

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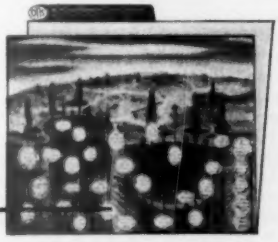

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Employment Notices

The JOURNAL will post notices of men and jobs available. Companies and AIME members are invited to use this space, for which there is no charge. Except as noted below, address replies to: Code (appropriate number), JOURNAL OF PETROLEUM TECHNOLOGY, 408 Trinity Universal Bldg., Dallas 1. Show return address on envelope. These replies will be forwarded unopened and no fees are involved.

Replies to the positions coded Y6129 and Y6084 below should be addressed to: Engineering Societies Personnel Service, 8 West 40th St., New York 18, N. Y. The ESPS, on whose behalf these notices are published here, collects a fee from applicants actually placed.

POSITIONS

♦ Engineers. (a) Engineer to assist chief engineer for oil exploration and production operations. (b) geologist to do necessary structural and stratigraphic research to find oil in the district. Location, Texas. Y6129.

♦ Engineer who is capable of setting up department and running manufacturing angles of newly formed company in the lubricant line. Salary open. Location, New Jersey. Y6084.

♦ A southern university has an opening for a man to teach courses in petroleum and natural gas production engineering. It would be preferred that he have an MS degree but this will be waived in favor of adequate experience. Rank and salary will be based on the qualifications of the candidate. Code 536.

♦ (a) Research group leader and research engineer, 26-40. BS and preferably a PhD in physical chemistry, physics, petroleum engineering, or chemical engineering. Should have experience in reservoir mechanics research, or fluid flow research. Will be responsible for research program in multiphase flow and other aspects of reservoir mechanics.
(b) Research engineer, 26-40, BS and preferably an advanced degree in petroleum or mechanical engineering. Must be widely experienced in well completion practices. Will be responsible for research program in well completion practices and well mechanics.
(c) Research metallurgist, 26-40. BS and preferably advanced degree in metallurgical engineering. Should have experience with all types of laboratory apparatus for metallurgical study and experience in selecting materials for all types of services. Corrosion studies, materials selection and analysis of failures will constitute the bulk of the work. Salaries open. Location, Ponca City, Okla. State age, experience, education and salary desired in opening letter. Write direct to Personnel Records Division, Continental Oil Co., Ponca City, Okla.

♦ Two research engineers, with MS degrees and two to five years' field experience are desired as permanent additions to an expanding staff. The work includes research in fundamentals of reservoir performance and secondary recovery, and involves application of newly developed reservoir engineering techniques in studies of foreign and domestic pools. Location, Tulsa. Address replies, giving full information, to: Chief of Research, The Carter Oil Co., P.O. Box 801, Tulsa, Okla.

PERSONNEL

♦ Reservoir engineer, age 31, married, seven years' experience in lab, field and reservoir evaluation studies. Desire position with progressive independent as reservoir evaluation engineer. Code 158.

★ ★ ★

1952 Dues Bills Now Being Mailed

Bills for 1952 AIME dues are being sent out from Institute headquarters by alphabetical groups in the closing three months of 1951. With the exception of the Petroleum Branch, those members whose names begin with "A" through "D" were to be mailed their statements in October, "E" through "J" in November; "K" through "P" in early December and "Q" through "Z" in late December. Bills to Petroleum Branch members were not sent out until after decision had been made at the fall meeting of the Branch regarding distribution of the statistics volume.

Although according to the bylaws the annual fee is not payable until Jan. 1, prompt payment will make it possible to issue membership cards promptly and to assure no interruption of the dispatch of 1952 publications. Mailing of some 20,000 bills must, of course, be preceded by a careful check to see that the amount of each is correct, which takes some little time in the aggregate. Also, the proper crediting of dues payments from the same number of members is a job of no mean magnitude, which can be accomplished much better if checks are received over a period of several months.

The statements are made out with the assumption that each member wishes to receive the same publications in 1952 as he did in 1951; if not, the member should correct the bill accordingly. Transactions volumes are billed to members at $3.50 each; annual subscriptions to one or both of the monthly journals in addition to the member's primary choice are $4 each.

Members are urged to return the complete bill in making remittances. When payment is made through a company or bank this is particularly necessary in order to identify the person to be credited and the coverage of the payment. ★ ★ ★

Bylaws Changes Voted By Board of Directors

All changes in the bylaws published in the August issue of this journal were voted by the Board of Directors at their meeting on Sept. 12 and became immediately effective. The only change made from the printed version is the addition, in Art. I, Sec. 8, of the phrase "without payment of registration fee" immediately after the words: "and be privileged to attend meetings of the Institute." In other words, no registration fee may be charged to student associates at any AIME meeting. Other changes voted include: granting a credit on the initiation fee for member or associate member of $2 for each year of continuous and continuing AIME membership as a student associate or junior member; standardizing the annual dues of student associates at $4.50, including an annual subscription to a journal; and extending the 33-year age limit for junior membership for those who have been in military service following World War II. ★ ★ ★

Patents

Continued from Page 22, Section 1

can be. Theory of operation or function of a machine likewise can not be patented.

2. Novelty. The subject matter to be patentable must be new, that is, different in some respects.
3. Utility. To possess utility a patent must be useful and must be capable of producing a result.
4. Invention must be present.

Lawlor concluded his talk by stating that records are invaluable for interference and infringement cases. These records must be properly dated and witnessed by another person familiar with the scope of the subject matter that is to be patented. ★ ★ ★

Utilization of Research

Continued from Page 17, Section 1

committee, consisting of the heads of several of the departments, which meets occasionally with the research directors to consider the overall nature of the projects being undertaken, and which reviews the budget of the research department bi-annually. Another sponsoring committee level consists of groups assigned to each project which usually include one or more operating superintendents, one or more division engineers, the research scientist and his supervisor. These committees meet quarterly to review the research and to make suggestions regarding its progress. Committees such as these have been found to be particularly effective in bringing about the "team thinking" discussed above, and in decreasing the time required to test new ideas in the field. With this system, it has been found that the research man is frequently being encouraged to bring his idea out for trial in the field, rather than having to convince someone that a test should be made.

Some companies have found that the preparation of lectures and color slides and even moving pictures presented in a non-technical fashion have been of great help in acquainting personnel in other departments with the progress and significance of research being undertaken by the company. Still others have found that frequent visits by research personnel to operating areas and similar visits to the research center by engineering and operating personnel have been valuable in increasing liaison.

A number of companies have found that by permitting newly acquired research personnel to spend a period of time as trainees in the operating and engineering departments, and by similarly arranging for operating and engineering trainees to spend part of their indoctrination program in research, an early foundation is established upon which to build a mutual confidence so important in the employee's relationship with his co-workers as he progresses through the company. The giving to experienced research men of special assignments in the engineering and operating departments for a several-months' period to work alongside other experienced personnel shows promise of enhancing "group thinking." Other mechanisms have also been tried. However, it is the writer's opinion that much yet remains to be accomplished in the developing of suitable means for improving liaison.

In conclusion, several means of improving utilization of research have been discussed. None of them is new. However, if the impression has been conveyed that the satisfactory utilization of new concepts, processes and materials is dependent upon their acceptance *by people* and if the reader has been caused to consider how he can improve the part he plays in this performance, then the objective of this paper will have been accomplished.

REFERENCES

1. Pyle, H. C.: Address before the Technical Forum, Pacific Petroleum Chapter, AIME (May 28, 1951). *Jour. Pet. Tech.* (July, 1951) Sec. 1, 18.
2. Zeder, James C.: *Chem. Eng.* (Aug., 1951) 58, No. 8, 258.

★ ★ ★

Official 1952 Nominees Declared Elected

No supplementary nominations for AIME officers for 1952 having been received by Sept. 1, the nominees of the official Nominating Committee are the only candidates in the field, and balloting of the Institute membership is unnecessary. Official announcement of the elections of those whose names were published in the July issue of this journal was to be made at the November 14 meeting of the Executive and Finance Committees.

★ ★ ★

E. L. DeGolyer Elected Honorary AIME Member

E. L. DeGolyer, world renowned geologist who heads the firm of DeGolyer and MacNaughton in Dallas, Tex., was elected an honorary member of the Institute at the meeting of the Board of Directors on Sept. 12.

Only 20 men may hold honorary memberships at any one time, and election to that coveted status is made only after careful consideration of a candidate's professional and scientific contributions to both the AIME and the industry which it serves.

Born in 1886 near Greensburg, Kansas, DeGolyer first worked under eminent geologists at the University of Oklahoma, where he received his BA in geology. Since that time, he has located producing oil wells in most important areas of the hemisphere.

In 1914 he became a member of the Petroleum Division of AIME. He served as chairman of the Division from 1923 to 1925, as president of the Institute in 1927, as a director in 1928 and 1929, and on various committees of the Institute throughout his membership. He has been a lecturer at Princeton University and the University of Texas and is a member or fellow of a number of scientific organizations in the United States and England.

★ ★ ★

Proposed for Membership, Petroleum Branch

Total AIME membership on Sept. 30, 1951, was 17,234; in addition, 2,521 Student Associates were enrolled.

ADMISSIONS COMMITTEE

Thomas G. Moore, Chairman; Carroll A. Garner, Vice-Chairman; George B. Corless, F. W. Hanson, Albert J. Phillips, Lloyd C. Gibson, R. D. Mallison, John T. Sherman. Alternates, A. C. Brinker, H. W. Hitzrot, Plato Malozemoff, Ivan Given, T. D. Jones, W. A. Clark, Jr.

Institute members are urged to review this list as soon as the issue is received and immediately to wire the Secretary's office, night message collect, if objection is offered to the admission of any applicant. Details of the objection should follow by air mail. The Institute desires to extend privileges but does not desire to admit persons unless they are qualified. Objections on applications should be received on the 15th of the month following publication in PETROLEUM TECHNOLOGY.

In the following list C/S means change of status; R, reinstatement; M, member; J, Junior Member; A, Associate Member; S, Student Associate; F, Junior Foreign Affiliate.

INDIANA

Gary — Pelzer, Harry L. (A).

LOUISIANA

Lake Charles — Reed, Milner L. (M) (C/S-A-M).

MICHIGAN

Ann Arbor — Williams, George B. (M).

MINNESOTA

Cromwell — Granlund, Walter E. (J) (C/S-S-J).

NEW YORK

Jackson Heights — Sladic, Matthew J. (R, C/S-S-J).

OKLAHOMA

Bealston — Carter, Gene A. (J) (R, C/S-S-J).
Oklahoma City — Bonifazi, Arthur W. (J); Cobb, George H. (M).
Seminole — Marty, James R. (M).
Tulsa — Craig, Forrest F., Jr. (J); Jeffrey Thomas J. (M) (R, C/S-J-M).

TEXAS

Alice — Moran, Joseph P. (M) (C/S-J-M).
Amarillo — Dudenhoeffer, Alfred J. (C/S-S-J).
Carthage — Trimble, Rob D., Jr. (M) (C/S-A-M).
Corpus Christi — Barfield, William G. (M) Caldwell, Robert G. (M).
Crane — Agnew, James W. (M) R, C/S-J-M).
Fort Worth — Wintle, Thomas H. (J) (R, C/S-S-J).
Kermit — Krottinger, Ralph L. (C/S-S-J).
Kilgore — Christianson, Edward G. (M) (R, C/S-J-M); Emrick, Omar L. (J) (C/S-S-J).
Lamesa — Prejean, Joseph S. (J) (R, C/S-S-J).
Lubbock — Main, T. Talmage, Jr. (J) (R, C/S-S-J).
McCamey — Green, Ira C. (J) (R, C/S-S-J).
Midland — Anderson, Edmund T. (M) (R) Odessa — Becker, William H. (J) (R,C/S-S-J).
San Antonio — Bowman, Richard J. (J) (R, C/S-S-J).
Victoria — Owens, Herman, Jr. (J).

BRITISH WEST INDIES

Jamaica — Hartman, James A. (J).

CANADA

Alberta — Dixon, Robert K. (J).

★ ★ ★

Book Reviews

Bibliography of Organic Reefs, Bioherms and Biostromes. Bibliography of Stratigraphic Traps

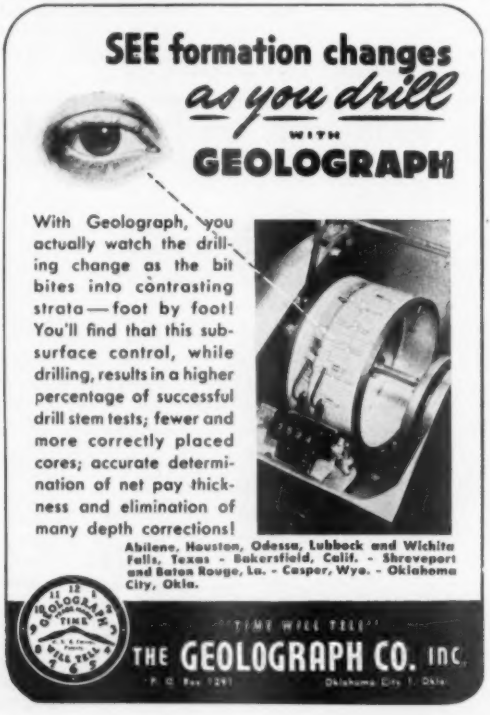
Edited by W. E. Pugh and B. G. Preston, compiled by Seismograph Service Corp., Tulsa, Okla., 1950, 1951. 139 and 195 pp., 9½ x 6¾ in., paper, free.

The 2,400 references listed in these two comprehensive bibliographies are presented in three cross-indexed sections — an Author Index, a Geographical Location Index, and a Geologic Age Index. The basic index is the Author Index, which compiles all geological references obtained, arranged alphabetically according to the author's name, giving the title and the best available sources for the reference. The reef bibliography also contains a subject index, and the stratigraphic trap bibliography is briefly annotated. The editors were aided in the compilation by the technical staff of SSC and by A. N. Murray and his staff at the Department of Geology, University of Tulsa.

Occurrence of Oil and Gas in Northeast Texas

Compiled by Bureau of Economic Geology of The University of Texas, and East Texas Geological Society, The University of Texas Publication No. 5116, Austin, Tex., 1951. 463 pp., diagrs., charts, maps, tables; 8½ x 11 in., cloth, $10.00.

A compilation of papers on 135 fields by 69 authors, this publication gives data on the location, history, occurrence of oil and gas in the reservoir rocks, stratigraphic and lithologic details, nature of trap, productive area, character of oil and gas recovered and production history.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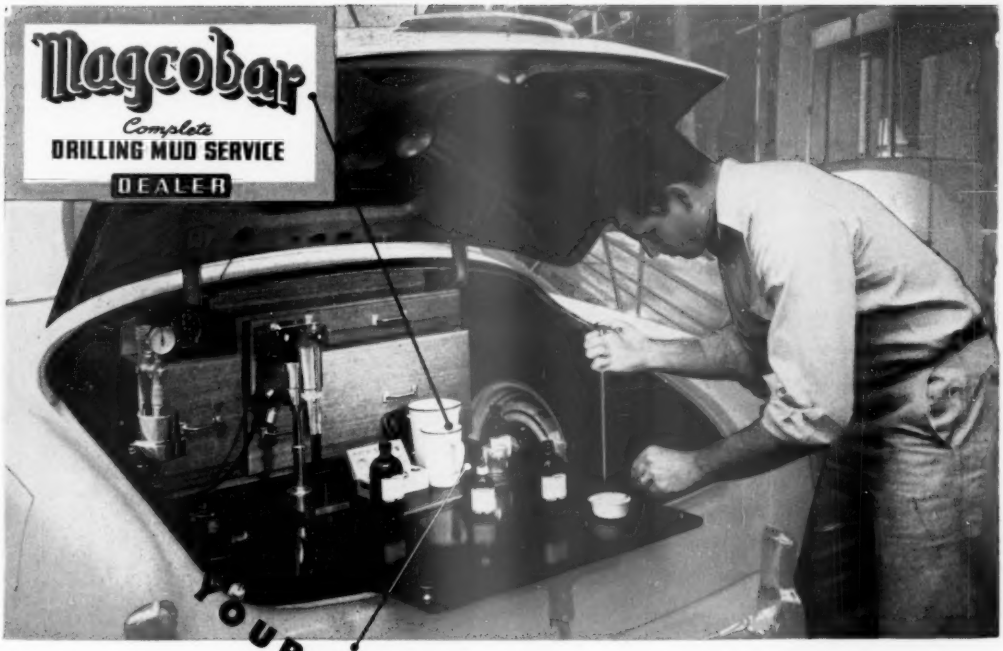

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